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Sustainable Biomaterials for Food Packaging

Edited by Sneh Punia Bangar, Kyle D. Dunno,
and William Scott Whiteside



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Considering the great demand for environmentally friendly packaging systems, researchers are developing solutions that consider the sustainability and economic feasibility of the process. ***Sustainable Biomaterials for Food Packaging*** evaluates the role of emerging biomaterials for food packaging systems and discusses in detail the various engineering aspects associated with packaging. The book also covers the environmental aspects, social perception, and acceptance of biomaterials packaging. It covers the sustainable packaging systems available for the preservation of all types of foods and products derived from meat, milk, fruits/vegetables, and baked goods. The book is suited for academicians, scientists, students, and food industry professionals; it will also satisfy the needs of researchers, scholars, and students at both the postgraduate and undergraduate levels.

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Preface

With the growing awareness about environmental issues, the demand for renewable and biodegradable materials as an alternative to replace petroleum-based products is successfully gaining the attention of researchers and academics. Biomaterials are considered a remarkably versatile resource to replace petroleum-based packaging materials as they are easily accessible, stable, low-density, non-abrasive, non-toxic, renewable, and biodegradable. The global market for eco-friendly food packaging, estimated at US\$184.7 billion in the year 2022, is projected to reach a revised size of US\$319.4 billion by 2030, growing at a CAGR of 7.1% over the analysis period 2022–2030. Considering the great market demand for sustainable material-based packaging systems, it is high time researchers developed a suitable solution that considers the sustainability and economic feasibility of the process. A range of biomaterials, modified biomaterials, nanocomposites, and nanofiber-based materials have been developed for film/packaging matrices to protect a wide range of food products during storage. A comprehensive and critical review of available information in a book form that covers various types of foods is needed.

The book will evaluate the role of emerging biomaterials in enhancing the efficacy of food packaging systems and will discuss in detail the various engineering aspects associated with packaging. The book will also cover the environmental aspects, social perception, and acceptance of biomaterials packaging. This book will cover the sustainable packaging systems available for the preservation of all types of foods and products derived from meat, milk, fruits/vegetables, bakery, etc. It will evaluate the effect of all emerging and novel bioactive agents and the available materials and

biopolymers on the quality of all types of foods. The book chapters will be contributed by authors who are renowned researchers and experts in this field.

The book will provide the latest information to academicians, scientists, students, and the food industry. The book will satisfy the needs of researchers, scholars, and postgraduate and undergraduate students. [Chapter 1](#), contributed by Armin Fashi, Abbasali Zamani, Ali Fallah Delavar, and Nader Noshiranzadeh, discusses the history, characteristics, recent applications, analysis methods, regulatory requirements, global marketing, and future directions of sustainable packaging biomaterials. [Chapter 2](#) discusses the role of nanotechnology in widening the range of options for formulation and production of packaged functional products. Nano-based products exhibit oxygen scavenging ability, antimicrobial activity, catalytic activity, and various other properties due to their peculiar molecular and structural characteristics. This chapter highlights the recent technologies directed at improving composition, processing, and packaging using nano-based matrices. Further, the particle migration and toxicity imparted by these materials in food products, as well as the socio-economic and environmental aspects concerning nanocomposite utilization, have also been discussed. [Chapter 3](#) discussed the aliphatic polyester, including polylactic acid (PLA), polycaprolactone (PCL), polybutylene succinate (PBS), and polyhydroxyalkanoate (PHA), and highlighted their specific applications in food packaging. [Chapter 4](#) outlines the aspects, including the advancements of protein-based biopolymers in food packaging, their properties, extraction, synthesis, and industrial applications in food packaging. Moreover, current challenges associated with protein-based biopolymers and future approaches that can be beneficial in overcoming these issues are elaborated. [Chapter 5](#) provides a comprehensive review of recent developments in the application of biomaterials in active packaging. The classification of active packaging based on its functions is discussed. The research status of biomaterials (natural sources, chemical synthesis, or microbial synthesis) that serve as film-forming matrices or functional ingredients for the development of active packaging is reviewed. Current

research on the application of active packaging in food preservation, as well as the challenges and future research trends, is also discussed. [Chapter 6](#) explores the emerging trends and advancements in utilizing active biomaterials for creating sustainable, intelligent packaging solutions. It offers a detailed overview of key biomaterials, such as polysaccharides, proteins, and lipids, highlighting their potential to enhance food safety and shelf life. The chapter delves into smart packaging, covering technologies like pH indicators, gas sensors, enzyme-responsive systems, and temperature-sensitive materials. It further discusses real-world applications across dairy, meat, and fresh produce sectors while addressing consumer awareness, regulatory aspects, challenges, and future directions for biomaterial-based smart packaging innovations. [Chapter 7](#) is written by Prof. Arun Prasath V and his team from the Department of Food Process Engineering, National Institute of Technology Rourkela, Odisha, India. The chapter explores bio-based inks and dyes for food packaging, focusing on sustainable alternatives derived from renewable resources like plants and microorganisms and their roles in active and intelligent packaging (like pH indicators or antimicrobial agents). [Chapter 8](#) is written by Venkata Giridhar Poosarla, Aparna Ramadoss, and Shaik Sadiya and discusses the development and application of sustainable biomaterials for packaging fresh meat and meat products. This chapter provides a comprehensive overview of the utilization of biodegradable materials, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), polysaccharides, and proteins in the formation of smart packaging films, which are being employed on meat and meat products to reduce environmental impact by maintaining the quality, safety, and extending the shelf life. It mainly focuses on the film's functional attributes, such as physical, barrier, mechanical, thermal, structural, and morphological properties. Integrating active and intelligent packaging technologies is also explored in detail to enhance food preservation further, thereby monitoring shelf life. This chapter aligns sustainability and functionality, offers valuable insights into the future of meat packaging, and supports the ongoing transition toward environmentally responsible food systems. [Chapter 9](#) provides a critical

analysis of sustainable biomaterials applied to dairy packaging, focusing on natural polymers, dairy-derived proteins, and biodegradable synthetic polymers. It examines their mechanical and barrier properties, advances in biocomposites and nanotechnology, regulatory frameworks, and the environmental and economic implications of adopting sustainable solutions within the dairy industry. [Chapter 10](#) presents a comprehensive overview of the use of biomaterials as a sustainable alternative to conventional plastic packaging. The chapter discusses the main types of biopolymers applicable to the packaging of fruits and vegetables, their functional properties, technological barriers, and the most recent advances in the area, such as the use of plant residues and nanocellulose. The approach reinforces the importance of the circular economy and innovation to reduce post-harvest losses and the environmental impacts of the food production chain. Samandeep Kaur, Vikrant Singh, and Parmjit S. Panesar contributed to [Chapter 11](#) and summarized recent advancements in the development and application of sustainable biomaterials for bakery product packaging. The chapter discusses the key factors influencing bakery shelf life, evaluates conventional and innovative packaging technologies, and highlights the role of biopolymers and bioplastics in enhancing barrier, antimicrobial, and mechanical properties. It further addresses challenges, environmental impact assessments, and future directions for promoting sustainable solutions in the bakery industry. Consumers' perception and acceptability of sustainable packaging systems are critical for the success of designing packaging with the end in mind. [Chapter 12](#) illustrates consumer perceptions and acceptability toward sustainable packaging systems, differences across generations, and how these are affected by regulations.

About the Editors

Sneh Punia Bangar is Assistant Professor in the Department of Packaging Science and Graphic Media at Rochester Institute of Technology, New York. Prior to this appointment, she worked as a postdoctoral researcher in the Department of Food, Nutrition, and Packaging Sciences at Clemson University, SC, USA. Her research focuses on the design and development of sustainable biopolymer-based films, coatings, and packaging materials derived from starch, cellulose, lignin, and other natural polymers. A key aspect of her research is adding value to agricultural and food industry waste by extracting functional biopolymers with applications in food and packaging. She has authored or co-authored more than 100 research/review articles, 15 authored/edited books, 35 book chapters, and 20 conference proceedings/seminars. Currently, she is the Associate Editor of the *Journal of Food Measurement and Characterization* (Springer), an editorial board member of the *International Journal of Food Science and Technology* (Wiley), Academic Editor of the *Journal of Food Quality* (Hindawi), and a Section Editor of *Current Food Science and Technology Reports* (Springer). Her significant contributions to academia and research were acknowledged with the “Award of Honour” in 2019 for her outstanding achievements. She is the recipient of the GSG Outstanding Graduate Research Assistant (2022) and CAFLS Outstanding Graduate Student Research Award (2023) at Clemson University, USA. Dr. Bangar received the “Professor Gurcharan Bains Award” from the Association of Food Scientists & Technologists (India) in 2023 for her incredible contribution to Food Science and Technology. Also, she has been listed (2023 and 2024) in “World Ranking of Top 2% Scientists,” published by Stanford University, USA. Dr. Bangar

was awarded the recipient of Clemson University's Distinguished Post-Doctoral Fellow Award for 2024. She has an H-index of 62 with ~13000 citations, as per Google Scholar.

Kyle D. Dunno is Associate Professor and Chair of the Department of Packaging and Graphic Media Science at the Rochester Institute of Technology (RIT), NY, USA. His research focuses on the distribution of food products within the supply chain, with particular emphasis on how transportation hazards—such as shock, vibration, and compression—affect food quality and contribute to food loss. Dr. Dunno has authored or co-authored over 30 peer-reviewed journal articles and numerous conference proceedings and holds multiple patents in the field of packaging science. He serves as Co-Editor-in-Chief of the *International Journal of Advanced Packaging Technology*. He is an active reviewer for several leading journals, including *Packaging Technology and Science*, *Food Packaging and Shelf Life*, and *Postharvest Biology and Technology*. He is a Certified Packaging Dynamics Professional and serves on the Global Board of Directors of the International Safe Transit Association, where he has also held leadership roles within the Certification Council and Technical Division. His work continues to advance the development of innovative packaging systems that enhance product protection and sustainability throughout the supply chain. Dr. Dunno earned his Ph.D. in Food Technology, M.S., and B.S. in Packaging Science from Clemson University.

William Scott Whiteside is Professor in the Department of Food, Nutrition, and Packaging Sciences at Clemson University, USA. With a background in food technology and agricultural sciences, he has over 25 years of experience working on ways to process and package food safely. William Scott Whiteside has expertise in food safety, thermal food processing, food product shelf life, and food packaging. He also leads the Cryovac® Retort Lab, a teaching, research, and service facility that provides a wide range of services, including food processing and packaging, all at one location. He has taught a variety of short courses and

delivered presentations across the United States and internationally on topics such as packaging design, food safety, retort and thermal processing, biopolymer packaging, and confectionery packaging. Recognized as a thermal process authority by the FDA and USDA, William Scott Whiteside is frequently consulted by food companies around the world. He has published over 75 scientific papers and holds a patent for innovative food packaging technology. In addition to his teaching and research, he is an active member of leading professional organizations, including the Institute of Food Technologists (IFT), the Institute for Thermal Processing Specialists (IFTPS), and the International Association for Food Protection (IAFP).

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Introduction of Sustainable Biomaterials

1

Armin Fashi, Abbasali Zamani, Ali Fallah Delavar,
and Nader Noshiranzadeh

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1.1 EVOLUTION OF FOOD PACKAGING

The safety and quality of food products have consistently represented a paramount concern in the food industry. In the year 2015, an estimated 600 million people were impacted by foodborne diseases, and with the expansion of international trade, the likelihood of such illnesses proliferating has escalated, underscoring the imperative for enhanced food safety protocols ([Bahrami et al., 2020](#)). Food packaging functions as an all-encompassing system that preserves the quality, safety, and integrity of food products throughout the steps of transportation, distribution, storage, and retail until consumption occurs. The materials employed for packaging safeguard food against contamination from air and microorganisms, thereby averting ingredient degradation and prolonging its shelf life ([Kumari et al., 2024](#)). Furthermore, packaging assumes a pivotal role in establishing brand identity, marketing, and promotional endeavors. The architecture of food packaging constitutes a vital element of a corporation's marketing strategy,

guaranteeing product durability while facilitating its differentiation within the marketplace ([Ares et al., 2022](#)).

The historical progression of food packaging, from ancient times to the present ([Kumari et al., 2024](#)), is illustrated in [Figure 1.1](#). Gradually, with the augmented significance of food preservation, a diverse range of materials has been utilized in the field of packaging. These include natural substances such as gourds, leaves, and bamboo, as well as more advanced materials like clay jars, glass, paper, metal, cardboard, and various synthetic and natural polymers. In ancient Egypt, glass was used to store food and liquids, while in China, around the 2nd century BC, the flexible packaging method was developed. These innovations have greatly influenced the packaging industry. During the Middle Ages, wooden barrels were commonly used, and in the 19th century, the invention of metal cans and the first paperboard box revolutionized the preservation and transportation of food. After World War II, remarkable advancements in plastics further transformed food packaging, leading to significant changes in how products were preserved and stored. These developments not only improved the quality and longevity of food but also introduced consumers to brand-focused and need-based packaging solutions ([Kumari et al., 2024](#)).

The food supply chain involves various types of packaging, which can be classified into primary, secondary, and tertiary levels. Primary packaging refers to materials in direct contact with the food, secondary packaging groups primary packages together, and tertiary packaging involves the grouping of multiple secondary packages. Recent market evaluations indicate that the predominant materials employed for food packaging consist of petroleum-derived plastics, glass, metal, and paper/cardboard ([Khandeparkar et al., 2024](#)).

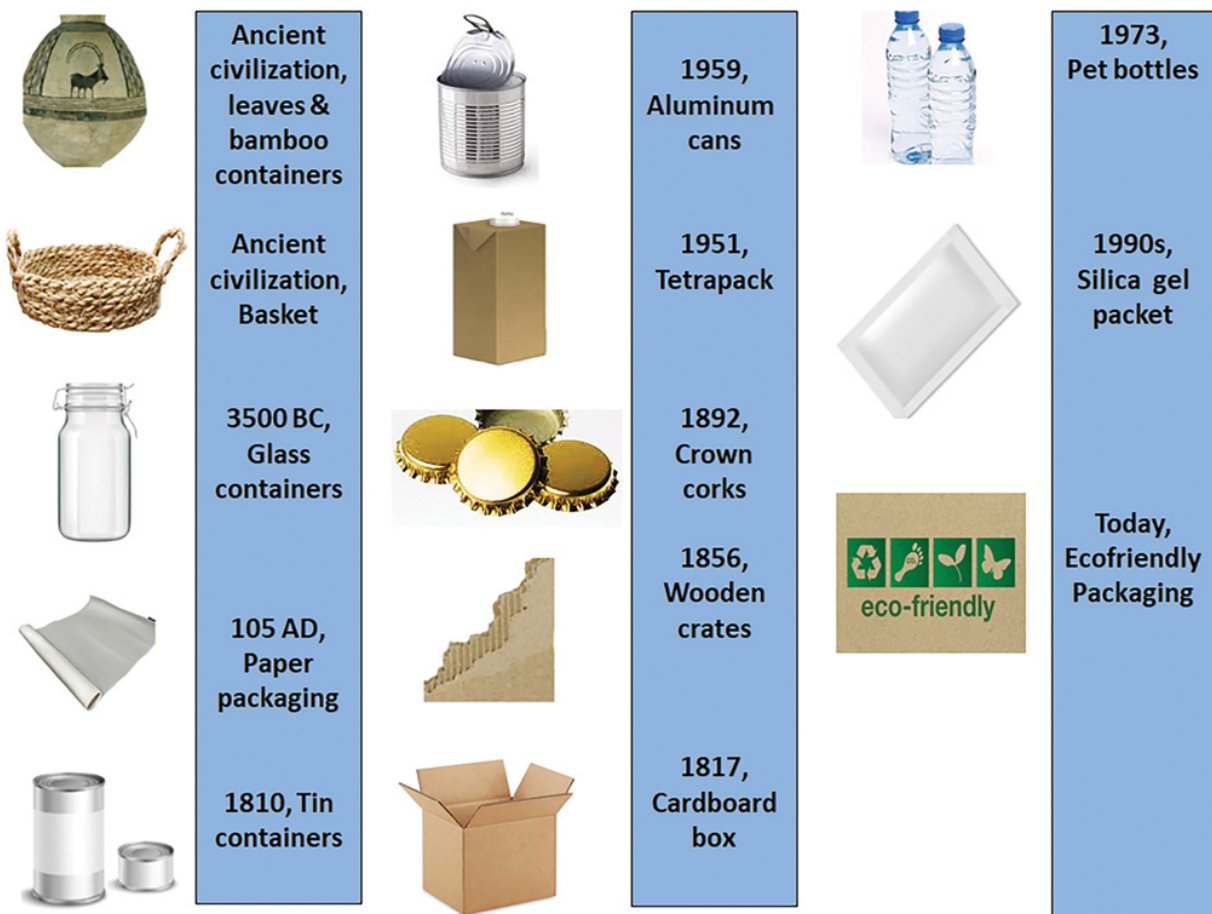


FIGURE 1.1 Time evolution of food packaging. [↗](#)

According to the latest scientific research ([Pangarkar, 2025](#)), paper and cardboard prevail in the packaging sector, possessing a global market share of 33.2% ([Figure 1.2](#)). Flexible plastics closely trail, constituting 25.5% of the market, thereby underscoring their extensive application across numerous packaging applications. Rigid plastics represent 18.7%, while metal packaging materials account for 12.1%. Glass packaging holds a market share of 5.8%, with alternative materials, such as biopolymers, comprising the remaining 4.7% of global demand ([Pangarkar, 2025](#)). Among these materials, plastics derived from petroleum (encompassing both rigid and flexible forms) possess the predominant market share, accounting for 44.2% of the aggregate. This dominance is fundamentally attributable to their scalability, economic efficiency, lightweight nature, multifunctionality, and convenient transportability. As reported by European

Union statistics, the annual output of petroleum-based plastics utilized for packaging reaches 23 million tons, with projections indicating an escalation to 92 million tons by the year 2050 ([Geyer et al., 2017](#); [Varžinskas & Markevičiūtė, 2020](#)). These plastics, which are synthetic polymers originating from natural gas or oil, find applications in various aspects of contemporary daily life. Their inherent structural stability inhibits natural degradation, thereby causing considerable environmental challenges. The complexities associated with waste management pertaining to traditional packaging materials, particularly plastics, are exacerbated by their extensive application and single-use designs. Consequently, this predicament has resulted in millions of tons of non-biodegradable plastic waste infiltrating marine environments and ecosystems, thereby imposing grave threats to biodiversity and disrupting natural habitats. Furthermore, the manufacturing processes of conventional packaging materials substantially contribute to greenhouse gas emissions, thereby intensifying the repercussions of climate change ([Perera et al., 2023](#); [Joe, 2025](#)).

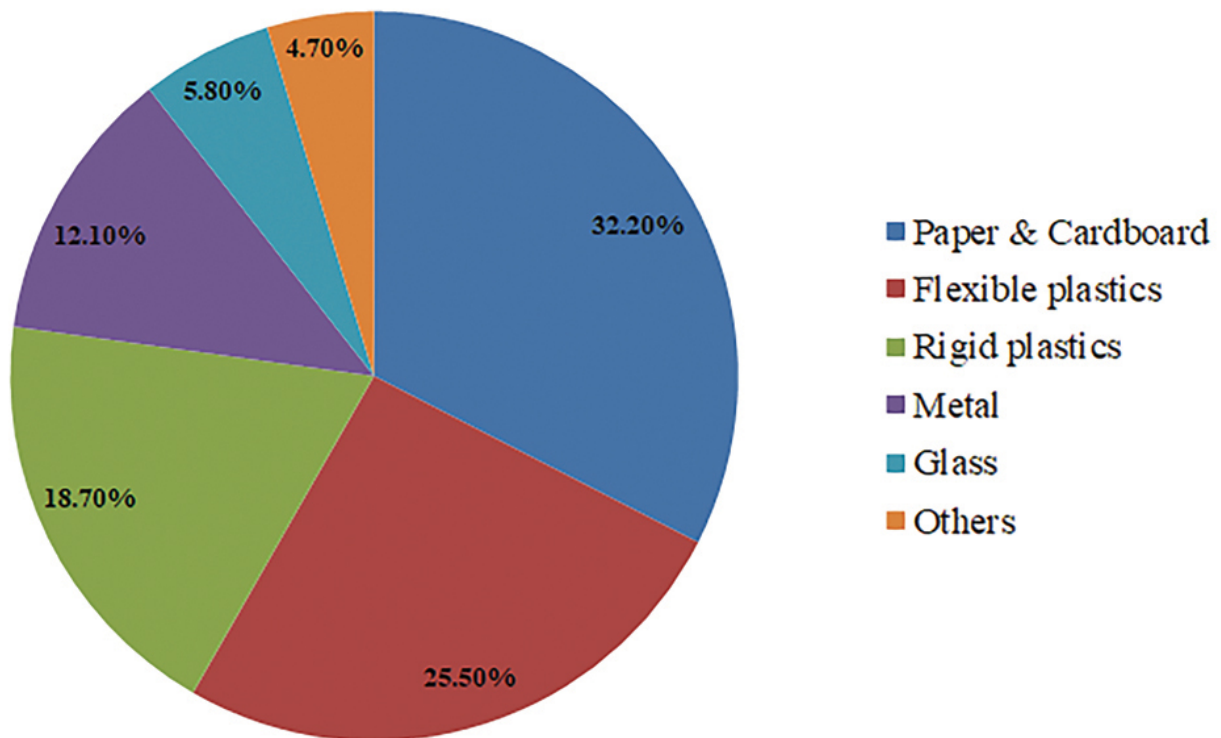


FIGURE 1.2 Global packaging demand distribution by material type. [↗](#)

Consequently, there exists an imperative for sustainable alternatives, such as biopolymers, that can alleviate these environmental impacts while concurrently fulfilling the functional requirements of food packaging. [Table 1.1](#) demonstrates a comprehensive overview of the pros and cons associated with the various materials employed in food packaging. Recently, the application of biopolymers in food packaging materials has garnered considerable global attention. Biopolymers present notable advantages over traditional plastics, encompassing renewability, biocompatibility, and biodegradability ([Varžinskas & Markevičiūtė, 2020](#); [Duarte et al., 2024](#)).

The transition toward biopolymers as a substitute for petroleum-based plastics in food packaging is predominantly motivated by two factors: (1) environmental concerns stemming from the escalating accumulation of plastic waste within nature and the global warming repercussions resulting from carbon dioxide emissions during the incineration of plastic waste, and (2) the limited and diminishing availability of petroleum resources. The biodegradability of biopolymers exhibits substantial variability contingent upon environmental conditions, including soil, marine, and composting environments ([Samir et al., 2022](#)). [Figure 1.3](#) illustrates the microbial degradation process of biopolymers in soil. However, the biodegradation rate of biopolymers is influenced by soil conditions. Both biological (biotic) and non-biological (abiotic) factors play a role in the complete degradation of organic materials ([Samir et al., 2022](#)). Biotic processes involve microorganisms breaking down the material, while abiotic factors such as photodegradation and chemical hydrolysis lead to physical and chemical degradation under extreme conditions like high temperatures or acidic/basic pH ([Samir et al., 2022](#); [Pooja et al., 2023](#)). However, one of the main challenges accompanying biopolymer-based food packaging is their relatively low mechanical strength and increased sensitivity to moisture, as shown in [Table 1.1](#). Despite these challenges, the growing adoption of biopolymers in food packaging highlights the necessity of scaling up the biopolymer industry. The following sections will focus on the various types of sustainable biomaterials and their importance in the food packaging industry, as well as explore innovative technologies such as nanotechnology

and smart packaging in this field. Additionally, consumer and regulatory requirements, as well as relevant testing protocols to ensure the performance and safety of bio-based packaging materials, will be examined.

TABLE 1.1 The Advantages and Disadvantages of Various Packaging Materials Used in the Food Industry ([Perera et al., 2023](#); [Kumari et al., 2024](#); [Khandeparkar et al., 2024](#); [Hussain et al., 2024](#)) ↵

<i>PACKAGING MATERIAL</i>	<i>ADVANTAGES</i>	<i>DISADVANTAGES</i>
Glass	(1) Non-reactive and safe for food (2) Excellent barrier properties (3) Recyclable and reusable	(1) Heavy and fragile; can break easily (2) Higher transportation costs (3) Energy-intensive production process
Metal	(1) Durable and provides an effective barrier against moisture, gas, and light. (2) Ease of handling, sterilization, transportation (3) Easily recyclable	(1) Metal packaging frequently contains trace metals like lead, tin, iron, cadmium, nickel, copper, zinc, and chromium, which are prone to migration (2) Heavier than other materials (3) Higher production costs
Paper/Cardboard	(1) Biodegradable and recyclable nature (2) Lightweight and easy to print (3) Cost-effective (4) Significantly lower environmental effect in comparison with other materials	(1) Poor barrier characteristics, low heat resistance, limited mechanical strength (2) Not suitable for all food types (3) Can become soggy or lose structural integrity (4) The migration of chemical compounds from the printed

<i>PACKAGING MATERIAL</i>	<i>ADVANTAGES</i>	<i>DISADVANTAGES</i>
		ink on paper packaging into the food matrix
Plastic	(1) Lightweight and flexible (2) Excellent barrier properties (3) Less expensive (4) Easy to transport	(1) Non-biodegradable, contributes to pollution, emission of greenhouse gases (2) May leach harmful chemicals into food (3) Limited sustainability compared to alternatives
Biopolymers	(1) Compostable and made from renewable sources (2) Reduced carbon footprint (the emission of greenhouse gases such as CO₂). compared to traditional plastics (3) Versatile and can be tailored for different needs (4) Excellent barrier properties (5) Good thermal properties - Less energy to produce	(1) Performance can vary; not suitable for all applications (2) Higher manufacturing costs (3) Limited availability and scalability (4) High sensitivity to moisture along with poor mechanical strength

1.2 DEFINITION AND IMPORTANCE OF SUSTAINABLE BIOMATERIALS

One of the principal obstacles confronted by the food industry relates to the formulation of an environmentally sustainable, economically viable, and sustainable packaging system ([Escobar et al., 2007](#); [Zoungranan et al., 2020](#); [Amin et al., 2021](#); [Khandeparkar et al., 2024](#)). Sustainable biomaterials are derived from renewable biological resources, which confer substantial environmental advantages by decreasing dependence on petroleum-derived plastics, minimizing waste generation, and lessening the carbon footprint associated with packaging production processes ([Perera et al., 2023](#); [Cancer et al., 2024](#)). Furthermore, these materials assist in extending the shelf life of food products, thereby alleviating food waste issues and improving food security. By endorsing responsible consumption and production frameworks, these biomaterials contribute to climate action (especially through the reduction of greenhouse gas emissions), promote economic advancement, and enhance public health outcomes.

Moreover, their integration encourages innovation, catalyzes job creation within local economies, and fosters social equity by offering opportunities for marginalized populations ([Ivonkovic et al., 2017](#); [Petrenko et al., 2024](#)). In the long term, the extensive application of sustainable packaging has the potential to markedly diminish environmental degradation, safeguard terrestrial and marine ecosystems, and propel the transition toward a more sustainable global food system. With the vigorous promotion of the United Nations Sustainable Development Goals (SDGs), the demand for eco-friendly packaging rises annually. Consequently, sustainable food packaging assumes a pivotal role in facilitating the realization of the 17 SDGs.

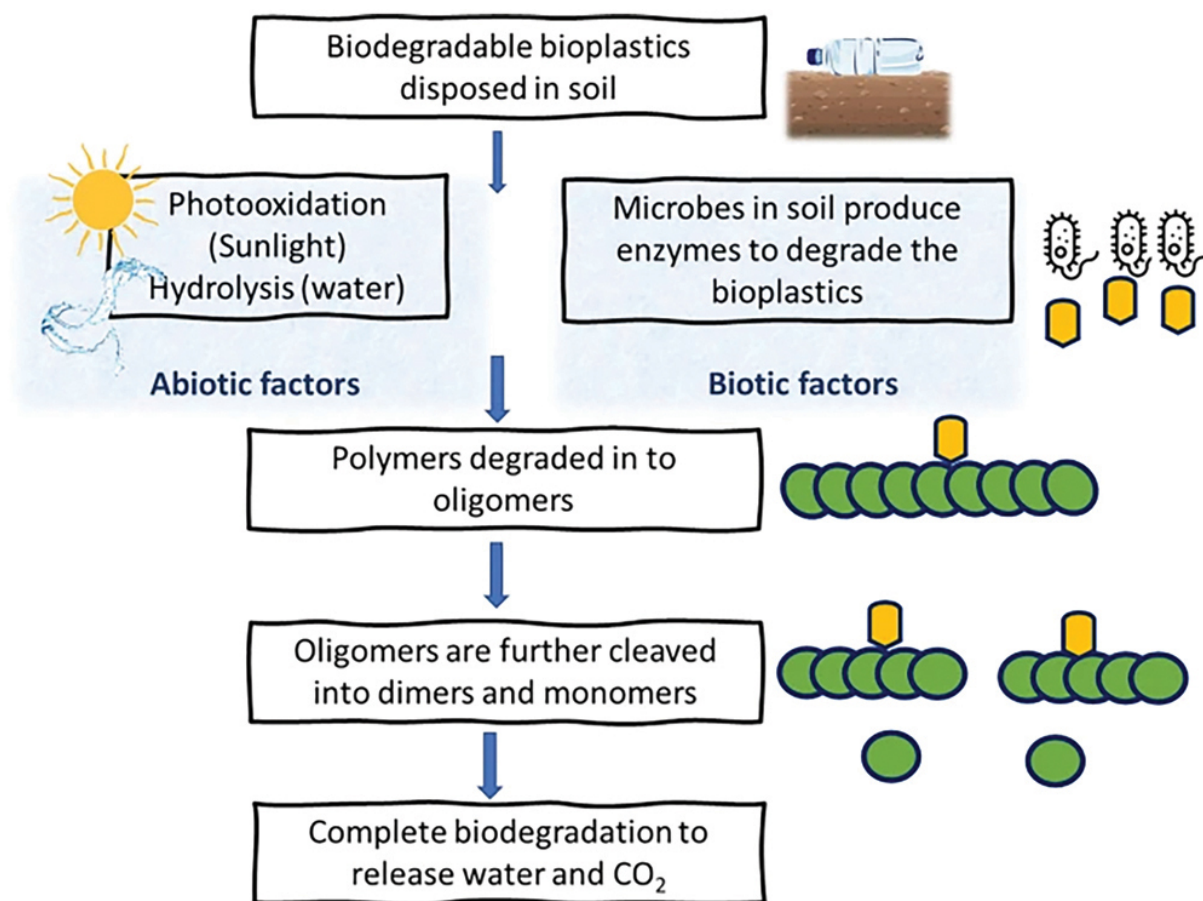


FIGURE 1.3 Consecutive steps of biopolymer degradation by microbes in the soil environment ([Pooja et al., 2023](#)). ↵

1.3 TYPES OF SUSTAINABLE BIOMATERIALS USED IN FOOD PACKAGING

Biopolymers are extensively employed in food packaging in the form of coatings and films ([Wang et al., 2022](#); [Gupta et al., 2022](#)). Coatings create a protective barrier directly on food products, thereby enhancing freshness and extending shelf life, while films function as distinct structures that provide barriers against moisture and contamination. Biopolymers can be categorized into three primary classifications ([Figure 1.4](#)) based on their

origin and production methodology ([Lisitsyn et al., 2021](#)): (1) directly extracted from biomass—these biopolymers are obtained directly from natural substances such as plants and animals. Illustrative examples encompass polysaccharides, proteins, and lipids; (2) synthesized bio-derived monomers—these biopolymers are synthesized from bio-based monomers extracted from renewable resources, such as plant oils or sugars, and subsequently polymerized into materials like polylactic acid (PLA); (3) produced by microorganisms—microorganisms, including bacteria and fungi, are utilized to synthesize biopolymers such as polyhydroxyalkanoates (PHA) and other microbial polysaccharides. The chemical structures of select biopolymers commonly utilized in food packaging are depicted in [Figure 1.5](#). The properties and potential applications of biopolymers, particularly concerning the development of edible packaging, have been summarized in [Tables 1.2–1.4](#).

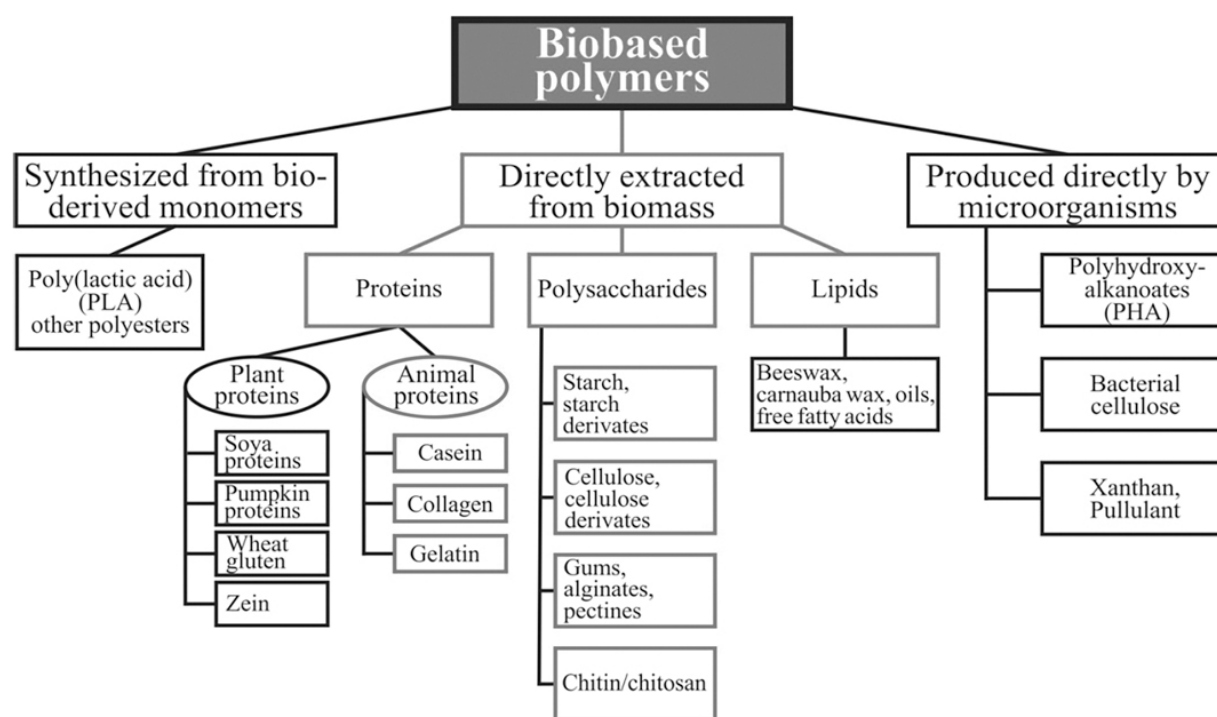


FIGURE 1.4 Schematic classification of different types of biopolymers ([Lisitsyn et al., 2021](#)). ↵

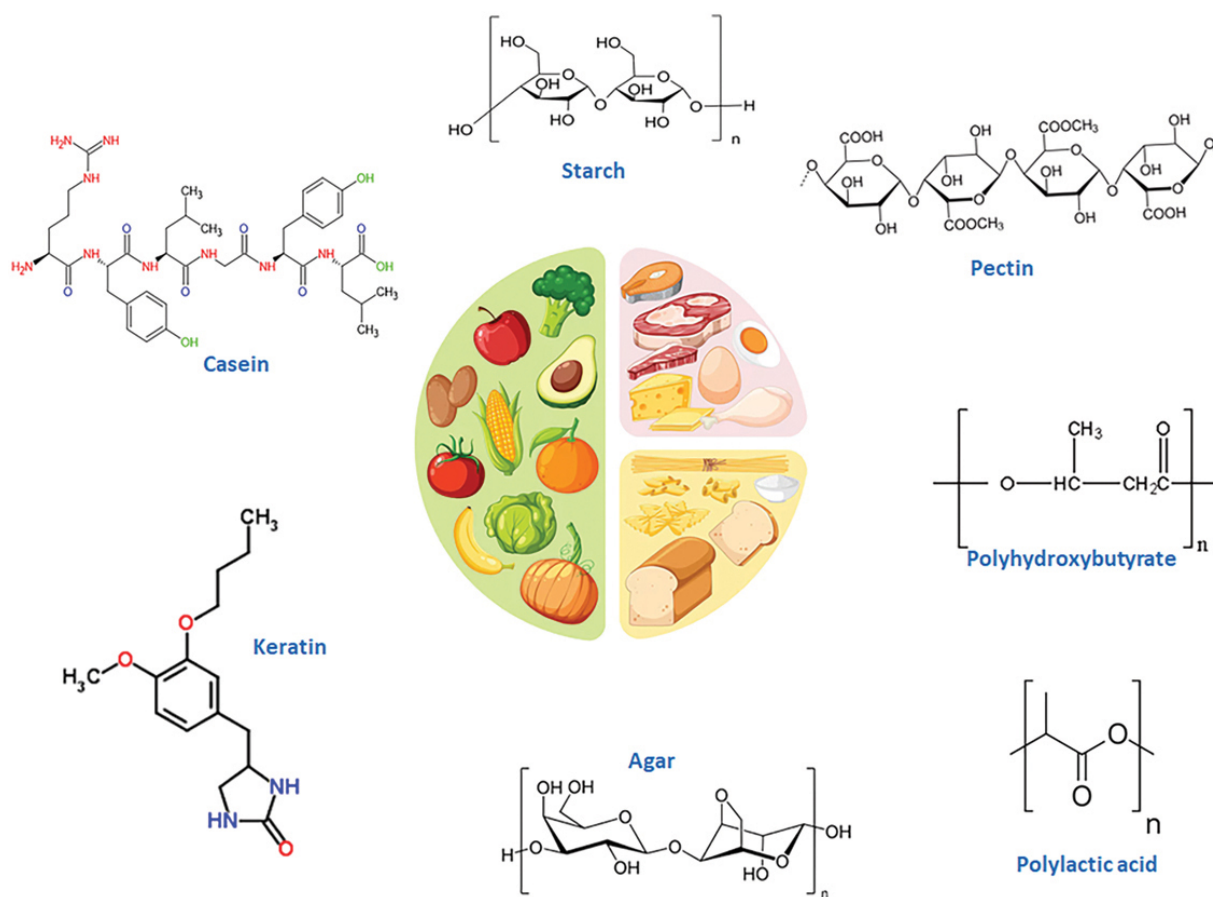


FIGURE 1.5 Chemical structure of some biopolymers involved in the development of food packaging. [↩](#)

1.3.1 Polysaccharides

Polysaccharides are macromolecules with high molecular weight, which facilitate the formation of dense, interconnected films through both intra- and intermolecular hydrogen bonding. These films demonstrate remarkable mechanical properties, including tensile strength and elongation, thereby rendering them an optimal choice for the formulation of edible films and coatings. Furthermore, these biopolymers are non-toxic and abundantly sourced from natural origins. They provide good barriers against gases like oxygen and carbon dioxide, but due to their hydrophilic nature, they are less effective in preventing the moisture loss of fruits.

To improve the performance of biodegradable films and coatings based on polysaccharides, different reinforcement agents are added to the

formulation, resulting in improved features in the design of packaging materials. These enhancements may involve the use of hybrid (composite) films, plasticizers, and nanoparticles (NPs) ([Lisitsyn et al., 2021](#); [Amin et al., 2021](#); [Perera et al., 2023](#); [Wu et al., 2024](#); [Leya et al., 2024](#)). Also, the incorporation of nutrients, antioxidants, antimicrobials, and color-changing indicators such as essential oils, plant extracts, and phenolic compounds into polysaccharides makes them attractive for the development of active and intelligent packaging systems, which can prolong the shelf life of food products, as detailed in [Sections 1.3.6](#) and [1.4](#). Starch, pectin, cellulose, chitosan, alginate, carrageenan, agar, lignin, and curdlan are examples of polysaccharide types. Applications and properties of these polysaccharides ([Table 1.2](#)) in food packaging systems have been reviewed in several scientific reports ([Lisitsyn et al., 2021](#); [Amin et al., 2021](#); [Perera et al., 2023](#); [Wu et al., 2024](#); [Leya et al., 2024](#)).

1.3.2 Proteins

Proteins are complex polymers formed by sequences of amino acids interconnected through peptide linkages. Each amino acid consists of a central carbon atom bonded to an amino group, a carboxyl group, a hydrogen atom, and a distinctive R group. Proteins can naturally occur as either fibrous or globular structures ([Akhila & Badwaik, 2022](#)). They are categorized into two principal classes according to their source: plant-derived proteins (including gluten, zein, pumpkin protein, and soy) and animal-derived proteins (such as casein, gelatin, whey, keratin, and collagen) ([Amin et al., 2021](#)). These protein-based substances are biodegradable and are commonly used in the production of edible films and coatings. Research has indicated that proteins typically exhibit superior mechanical properties compared to polysaccharides due to their unique structural characteristics, which provide excellent barriers against aromas and oils. However, when compared to composite polymers, protein-based materials tend to have lower mechanical strength and higher water vapor permeability ([Zhen et al., 2021](#)). Various protein-based polymers, including

whey protein, gelatin, wheat gluten, corn zein, and soy protein, have been effectively utilized in the production of edible films for food packaging, resulting in the augmentation of both their mechanical and barrier properties. Furthermore, biopolymers such as keratin, casein, zein, gelatin, and soy protein are integral to the manufacturing of a diverse array of industrial products, encompassing shopping bags, protective films, and sanitary items. The mechanical properties and overall performance of these protein biopolymers can be significantly improved through the incorporation of other biopolymers (both proteinaceous and non-proteinaceous) via the addition of active compounds and reinforcing agents (see [Sections 1.3.6](#) and [1.4](#)), as outlined in [Table 1.3](#).

1.3.3 Aliphatic Polyesters

Aliphatic polyesters represent a major category of biodegradable polymers known for their excellent processability, environmental degradability, and biocompatibility properties. These polymers are synthetically produced from renewable, bio-based monomers using traditional polymerization techniques ([Milani & Dehghan, 2024](#); [Marasinghe et al., 2024](#)). Structurally, polyesters consist of long molecular chains made up of ester linkages, which are the result of reactions between alcohols and carboxylic acids. Two primary synthesis methods used in their production are polycondensation and ring-opening polymerization. Depending on the application, aliphatic polyesters can be classified into homopolymers—composed of repeating units of a single type of monomer—and copolymers, which incorporate two or more different monomer units ([Milani & Dehghan, 2024](#); [Marasinghe et al., 2024](#)). Due to their thermal stability, effective gas barrier properties, and flexibility in being formed into films and coatings, these materials are widely utilized in food packaging. Their susceptibility to hydrolytic degradation, attributed to the ester bonds in their flexible backbones, facilitates easy biodegradation. Some aliphatic polyesters used in food packaging include polylactic acid (PLA), poly(butylene adipate-co-terephthalate) (PBAT), polyhydroxyalkanoates

(PHA), polybutylene succinate (PBS), polyhydroxybutyrate (PHB), and polycaprolactone (PCL). A summary of their properties and applications is presented in [Table 1.3](#).

TABLE 1.2 Features of Polysaccharides and Their Application in Food Packaging ([Amin et al., 2021](#); [Perera et al., 2023](#); [Leya et al., 2024](#); [Hussain et al., 2024](#)) ↵

PACKAGING MATERIAL	CHARACTERISTICS	APPLICATION
Polysaccharides		
Starch-cinnamon essential oil matrix incorporated with titanium dioxide nanoparticles	(1) Increased water vapor permeability (2) Reduced barrier features (3) Strong antimicrobial activity against <i>S. aureus</i> , <i>E. coli</i> , <i>S. typhimurium</i> (4) Superior mechanical features	Active packaging materials to maintain quality and extend the shelf life of fresh pistachios
Chitosan-titanium dioxide nanoparticles	(1) Photodegradation activity against UV light (2) Delaying ripening process and changes in the quality of tomatoes	Active packaging material for climacteric fruit
Carrageenan—copper monosulfide (CuS) nanoparticles	(1) Improvement of mechanical and thermal characteristics (2) Strong antimicrobial activity against <i>S. aureus</i> and <i>E. coli</i>	Active food packaging for beef by reducing microbial growth
Carboxymethyl cellulose-chitosan-zinc	(1) The improvement of antimicrobial activity	Antimicrobial active packaging material for

<i>PACKAGING MATERIAL</i>	<i>CHARACTERISTICS</i>	<i>APPLICATION</i>
oxide nanoparticles	(2) Reduction in water vapor permeability	bread
Agar-sugarcane wax-butterfly pea flower extract	(1) Visual color change in the presence of ammonia vapors at a pH range of 2–12 (2) The improvement of physical and mechanical properties	Intelligent packaging material shrimp (freshness optical tracking)
Alginate-aloe vera–garlic oil	(1) Boosted mechanical and thermal properties (2) Increased antimicrobial properties and UV barrier features (3) Extended shelf life	Edible coating for tomato
Gellan gum-purple sweet potato anthocyanins	(1) Enhanced antioxidant activity (2) The increased resistance to moisture and enhanced mechanical properties (3) The decrease in water vapor transmission rates (4) Poor hydrophilicity and swelling features	Intelligent packaging material to identify the spoilage of protein foods

TABLE 1.3 Characteristics and Food Packaging Applications of Proteins and Aliphatic Polyesters ([Amin et al., 2021](#); [Perera et al., 2023](#); [Leya et al., 2024](#); [Hussain et al., 2024](#)) ↵

<i>PACKAGING MATERIAL</i>	<i>CHARACTERISTICS</i>	<i>APPLICATION</i>
Proteins		
Gelatin-black rice bran anthocyanins (BACNs)-oxidized chitin nanocrystals (Ch)	(1) UV–vis light barrier (2) Improvement of antioxidant activity	Intelligent packaging material for freshness monitoring of (color variations) shrimp and hairtail
Keratin/citric acid	Enhancement of (1) biocidal effect, (2) transparency, and (3) elongation value (4) Extended shelf life	Active packaging material for carrot preservation
Whey protein– <i>furcellaran</i> –yerba mate–white tea extracts	(1) Decreased microbial growth (2) Improvement in factors such as solubility and water vapor permeability, tensile strength, and water content (3) Strengthened mechanical properties and increased thermal stability	Edible film packaging for cheese
Chitosan—Zein <i>Cinnamodendron dinisii</i> Schwanke oil	(1) Increased antioxidant activity level (2) Enhanced antimicrobial activity	Food packaging for preserving the color of ground beef
Aliphatic polyesters		
PLA-thymol-curry—kesum	Improvement in (1) thermal stability (2) water vapor barrier, and (3) antimicrobial activity against <i>S. aureus</i>	Active packaging material for preserving fruits,

<i>PACKAGING MATERIAL</i>	<i>CHARACTERISTICS</i>	<i>APPLICATION</i>
	and no antimicrobial activity against <i>E. coli</i> (4) Extended shelf life	vegetables, and meats
Poly(butylene adipate terephthalate) (PBAT)—glycerol—zeolite—cassava starch—citric acid	(1) Enhancement of mechanical and water vapor permeability properties (2) Preserved color and vitamin C levels during 7 days	Packaging material for broccoli florets (label indicator was able to detect carbon dioxide)
PLA-Poly (butylene succinate adipate) (PBSA)	(1) Increased mechanical strength (2) Improved antibacterial and antioxidant features (3) Prolonged the shelf life	Active packaging material for fishery products
Polyhydroxybutyrate (PHB)/graphene nanoplatelets	(1) Improved degradation temperature and barrier features (2) Antimicrobial activity against <i>Lactobacillus plantarum</i> (3) Increased shelf life	Active packaging material for processed meat

1.3.4 Lipids

Lipids are naturally derived from various sources, including insects, animals, and plants. This diverse group encompasses natural waxes (like beeswax, carnauba wax, and paraffin wax), oils, fatty acids, and neutral lipids (including shellac, coumarin, and turpentine). Owing to their hydrophobic nature, lipids exhibit excellent moisture barrier properties,

effectively protecting food products from spoilage. As a result, lipid-based films and coatings offer strong water resistance and are predominantly applied as surface coatings for fruits and vegetables to preserve their gloss and visual appeal ([Leya et al., 2024](#); [Wu et al., 2024](#)). However, due to their inherent lack of flexibility, lipid films and coatings are often mixed with other biopolymers to form composite structures with enhanced mechanical strength and barrier performance (see [Table 1.2](#), [Table 1.3](#), [Table 1.4](#)).

1.3.5 Composite (Hybrid) Biomaterials

Composite edible films and coatings are formulated by combining two or more biopolymeric materials, typically selected from proteins, polysaccharides, and lipids. These multi-component systems integrate the functional benefits of each individual component, thereby addressing the shortcomings associated with single-material films—particularly in terms of mechanical strength and barrier efficiency ([Zareie et al., 2020](#); [Leya et al., 2024](#)). Common types of composite structures include polysaccharide–polysaccharide, protein–protein, protein–polysaccharide, and protein–polysaccharide–lipid combinations. Various examples of such blended or composite films and coatings are provided in [Table 1.4](#).

TABLE 1.4 Properties of the Composited Biopolymers and Their Application in Food Packaging ([Amin et al., 2021](#); [Perera et al., 2023](#); [Leya et al., 2024](#); [Hussain et al., 2024](#)) ↵

PACKAGING MATERIAL	CHARACTERISTICS	APPLICATION
Zein-Gelatin-Tea Polyphenols	(1) Reduced the moisture loss, and (2) tea polyphenol addition prevented oxidative discoloration of fruits	Biodegradable films and coatings for fresh-cut kiwifruit, avocado, and banana
Alginate-Pectin	The preservation of their physicochemical characteristics compared to alginate-pectin-	Biodegradable films and coatings for mango fruits

<i>PACKAGING MATERIAL</i>	<i>CHARACTERISTICS</i>	<i>APPLICATION</i>
	coated samples and uncoated samples	
Tapioca and Potato Starches-Cellulose Nanofibers	Starches combined with various compositions of cellulose nanofibers provided better thermal stability	Biodegradable films and coatings for muffins
Chitosan-Beeswax	(1) Decreased metabolism and respiration of the products (2) The preservation of the physicochemical properties of the product during storage	Biodegradable films and coatings for strawberries
Gelatin-Frog Skin Oil	Frog skin oil addition in the gelatin decreased weight loss and maintained the physicochemical properties of the product during the storage step	Biodegradable films and coatings for persimmon

1.3.6 Biopolymer-Based Films and Coatings Combined with Additives

In order to enhance the functionality of edible films and coatings, various additives can be incorporated into biopolymers. Plasticizer is a common additive with low molecular weight that interacts with biopolymer matrix and increases the flexibility of films/coatings. Numerous plasticizers, such as glycerol, sorbitol, polyols, polyamines, and glucose, have been extensively studied and proven effective in enhancing flexibility, transparency, and mechanical properties and decreasing the water vapor transmission rate of edible films and coatings ([Amin et al., 2021](#); [Wu et al., 2024](#)).

Emulsifiers, another key class of additives, act as stabilizers by lowering the surface tension between two immiscible phases, facilitating the formation of stable emulsions. These emulsifiers help maintain a balance between hydrophilic and lipophilic components, preventing phase separation. While polysaccharide-based edible coatings and films are mechanically strong, they typically exhibit poor moisture barrier features. The inclusion of lipids in the film-forming solution significantly enhances the barrier performance of the film and coating-based packaging ([Amin et al., 2021](#); [Wu et al., 2024](#)). Considering the susceptibility of food products to microbial and fungal contamination, the incorporation of antimicrobial and antifungal agents into edible films and coatings may provide enhanced protective measures. Moreover, the integration of bioactive compounds such as vitamins, flavonoids, and antioxidants serves to elevate the nutritional profile, prolong shelf life, and augment the marketability of bio-based packaging materials ([Amin et al., 2021](#); [Wu et al., 2024](#)). An illustrative overview of biopolymers in food packaging is presented in [Figure 1.6](#) to elucidate the relationship between [Sections 1.3](#) and [1.4](#).

1.4 NEW RESEARCH IN FOOD PACKAGING

The application of nanotechnology and smart technology in sustainable packaging biomaterials signifies a critical advancement toward the creation of more effective, environmentally sustainable, and functional packaging solutions. By enhancing the characteristics of biomaterials, these pioneering technologies play a vital role in the development of packaging that is not only sustainable but also attuned to the requirements of consumers and industry stakeholders. As these technologies progress, they hold substantial promise for addressing the global issue of packaging waste and environmental sustainability. In this section, we will investigate the most recent advancements in these technologies, focusing on their transformative

impact on the packaging industry and their contribution to a more sustainable future.

1.4.1 Nanotechnology in Sustainable Food Packaging

The employment of biopolymers has demonstrated efficacy in prolonging the shelf life of food products. However, these materials frequently encounter obstacles, such as insufficient permeability, poor mechanical properties, and diminished resistance to moisture, which impede their extensive commercialization. To mitigate these challenges, the food packaging sector is actively pursuing innovative, state-of-the-art technologies. One of the most promising advancements in the field of sustainable packaging biomaterials is nanotechnology.

This interdisciplinary area concentrates on the design, manipulation, and fabrication of materials at the nanoscale, generally spanning from 1 to 100 nanometers. Nanotechnology enables the development of bio-nanostructured materials and nanocomposites through the modification of biopolymers, thereby enhancing the performance of sustainable bio-based packaging and ensuring the safety, quality, and extended shelf life of food products ([Mahmud et al., 2024](#); [Ghosh et al., 2025a](#), [2025b](#)). Bio-nanostructured materials consist of organic, biodegradable components that can be categorized into three primary classifications: polysaccharide-based (e.g., nanocellulose, nanostarch, and nanochitosan), protein-based (e.g., gelatin and pectin nanoparticles), and lipid-based (e.g., nanoliposomes and nano solid lipids) nanomaterials. These modified biopolymers exhibit essential characteristics such as flexibility, biocompatibility, and electrical conductivity. On the other hand, nanocomposites are created by combining biopolymers with inorganic nanomaterials like metals, metal oxides, ceramics, and minerals. Examples of such inorganic nanomaterials include silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO₂) nanoparticles, nanoclay, and carbon nanotubes (CNTs) ([Mahmud et al., 2024](#); [Ghosh et al., 2025a](#), [2025b](#)). The incorporation of nanoparticles into biopolymers, resulting in the formation of hybrid or nanocomposite materials, markedly

enhances the characteristics of packaging, including the enhanced mechanical strength, resistance to gases and moisture, and the capacity to serve as a barrier against microbial organisms. Despite the significant progress made, challenges remain, particularly regarding the potential migration of nanoparticles into food products, which could pose health risks in the short term. Nevertheless, promoting the use of biopolymer-based nanocomposites has the potential to reduce environmental problems, such as municipal waste generation, while also improving the durability of food products.

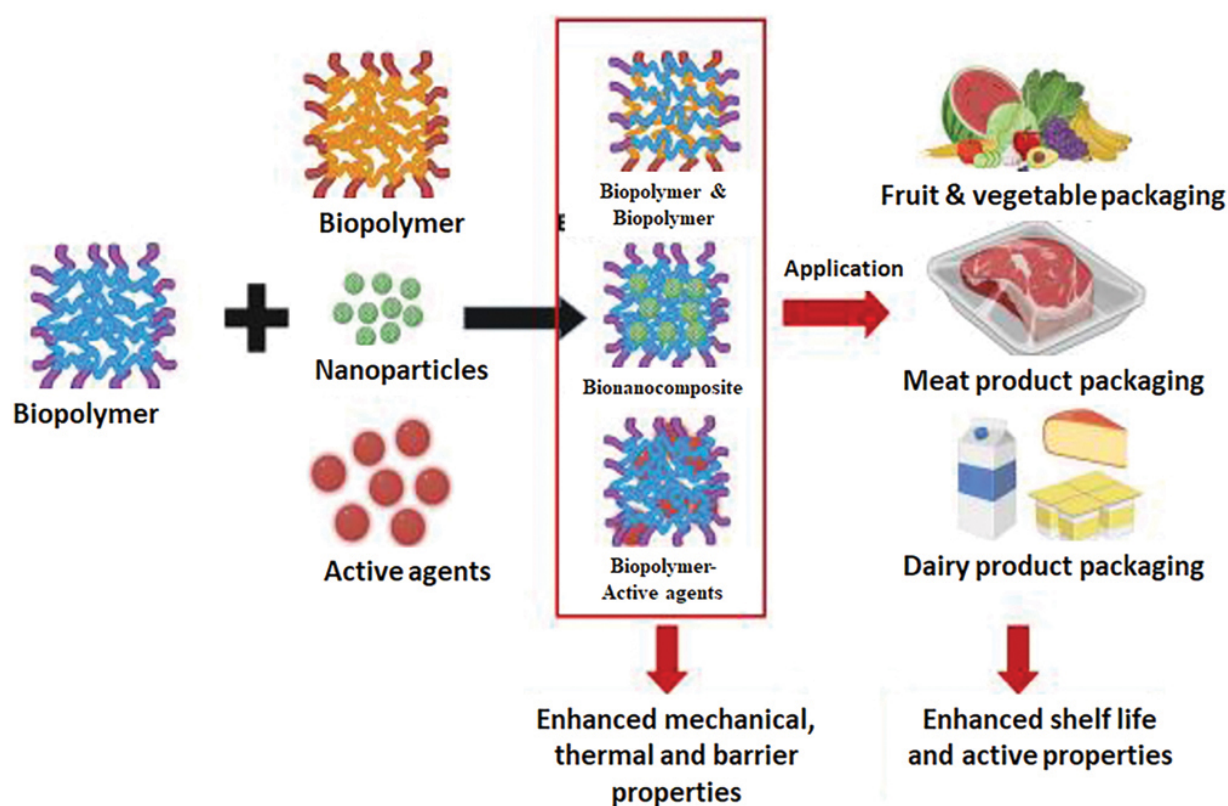


FIGURE 1.6 An overview of biopolymers in food packaging research ([Perera et al., 2023](#)). [↗](#)

A short overview of nanocomposite and biostructured materials used in bio-based packaging is summarized in [Table 1.5](#). Looking ahead, the adoption of bionanopolymers is expected to grow as part of the development of smart and intelligent packaging technologies, incorporating programmable, artificial intelligence (AI)-based materials into bioplastics.

The properties and applications of smart food packaging will be discussed in [Section 1.4.2](#).

TABLE 1.5 Features and Potential Applications of Nanostructured Material and Bionanocomposites Utilized in Food Packaging ([Ghosh et al., 2025a](#)) ↵

BIONANOPOLYMER	EXAMPLES	CHARACTERISTICS	APPLICATION
Bionanostructured materials	Polysaccharides (such as lignin, chitin, nanoparticles, etc.)	Improved antimicrobial property	Edible films and coatings in type of food products to extend their shelf life
	Protein nanoparticles (such as soy proteins)	(1) Superior antioxidant activity and (2) improved antimicrobial properties on foodborne pathogens	Edible food packaging
	Lipid nanoparticles (such as nanoliposomes)	(1) Moisture barrier (2) Oxygen barrier (3) Improved sensory and texture properties	Coating packaging material is used for a wide range of food products like confection pastries, and fruits

<i>BIONANOPOLYMER</i>	<i>EXAMPLES</i>	<i>CHARACTERISTICS</i>	<i>APPLICATION</i>
Bionanocomposites (hybrid nanoparticles)	Sodium alginate incorporated by Ag-SiO ₂ nanoparticles	The capability to control the levels of total soluble protein, total phenol, browning, and weight loss	A strong barrier against microbial growth

1.4.2 Smart Packaging

The escalating demand for fresh, healthy, and long-lasting shelf-life food products is driving innovations in packaging design. The primary objectives of smart packaging encompass the extension of prolonged shelf life, the minimization of food waste, and the enhancement of sustainability, offering both economic and environmental advantages ([Versino et al., 2023](#); [Du et al., 2025](#)). This cutting-edge technology can detect and transmit data from the packaged food, actively monitoring and controlling storage conditions.

While smart packaging results from integrating intelligent and active packaging technologies, it occasionally uses intelligent and active packaging technologies separately ([Versino et al., 2023](#)) ([Figure 1.7](#)). As an innovative solution, smart packaging streamlines the tracking of product information for both consumers and businesses ([Schaefer & Cheung, 2018](#); [Ghosh et al., 2025b](#); [Du et al., 2025](#); [Tshamisane et al., 2025](#)). [Table 1.6](#) outlines various bio-based active materials and intelligent systems, along with their applications in food packaging. Developments in active and intelligent packaging enhance food safety, quality, and consumer satisfaction while also creating promising opportunities for future advancements. Also, the introduction of active and intelligent packaging has resulted in the development of new concepts and materials, necessitating an updated regulatory framework for food contact materials. The global market for these packaging solutions is experiencing substantial expansion, with a projected compound annual growth rate (CAGR) of 5.5% from 2021 to

2030, culminating in an estimated market valuation of US\$38.66 billion by 2030 ([Versino et al., 2023](#)).

1.4.2.1 Active Packaging

The European Commission defines active compounds as substances that help extend shelf life or preserve/enhance the packaging environment. As per European Regulation No 450/2009, these active agents can be individual substances or combinations of substances ([Versino et al., 2023](#)). Examples of active substances include flavors, gas scavengers, antioxidants, antimicrobials, and light inhibitors, which are integrated into biopolymer matrices to create active food packaging ([Table 1.6](#)). Active packaging aims to protect the sensory and organoleptic properties of food from adverse external parameters like temperature, light, humidity, pressure, microorganisms, and gases like CO₂, O₂, and ethylene ([Day, 2003](#); [Biji et al., 2015](#); [Panja et al., 2018](#); [Versino et al., 2023](#)). It works by releasing or absorbing substances either from the food matrix or from the surrounding space within the food container. However, many active compounds can serve multiple functions, which complicates their classification.

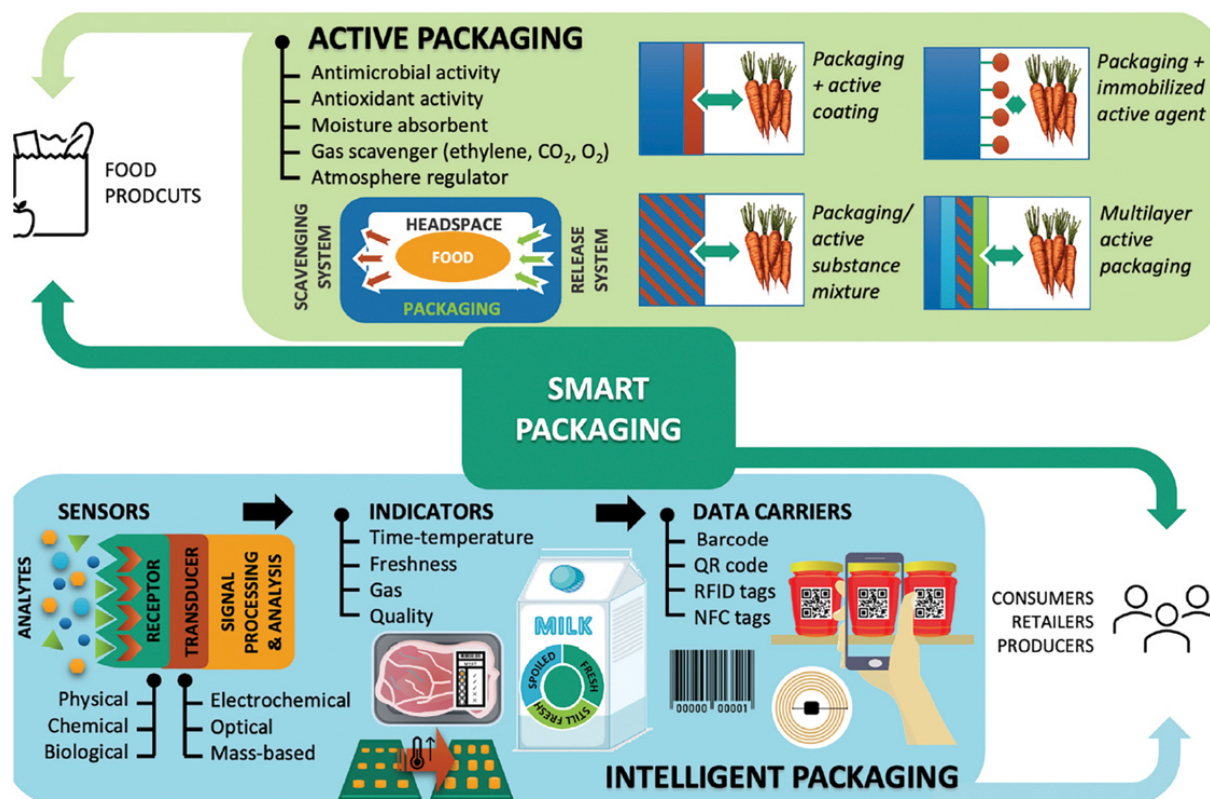


FIGURE 1.7 Classification of smart packaging (Versino et al., 2023). [↗](#)

TABLE 1.6 Some Active and Intelligent Films and Their Applications (Versino et al., 2023) [↗](#)

BIOPOLYMER	ACTIVE COMPOUND	USE
Active Biodegradable Films		
Soy protein isolate	0.5%wt Montmorillonite plus 0.5%v clove essential oil	Bluefin tuna fillets
Cornstarch	in situ green synthesis in the production of Ag nanoparticles	Cheese
Gelatin/Gellan gum	Red radish anthocyanins in different concentrations (5–20 mg/100 mL)	Fish and milk
PLA	1%wt Ag nanoparticles+ 3%wt TiO ₂ nanoparticles	Cheese

<i>BIOPOLYMER</i>	<i>ACTIVE COMPOUND</i>	<i>USE</i>
Intelligent Biodegradable Films		
Function	Innovative property	Use
Temperature sensor	A passive RFID tag modified with a copper-doped ionic liquid	Fresh food products for the detection of cold chain failures
pH-based freshness indicator	Biodegradable films encompassing anthocyanins from various sources Real-time freshness monitoring	(1) Meat products: fish, shrimp, beef, and pork (2) dairy products: cheese, yogurt,
Oxygen indicator	UV-light-activated oxygen-sensitive biofilm, along with the indicator of methyl blue	Food items packed in a modified atmosphere
Humidity indicator	Colorimetric sensor-based on photonic cellulose nanocrystals	Cereals, grain, and seeds

Active packaging can be broadly divided into two groups: (1) non-migratory packaging, which avoids the intentional migration of substances, and (2) controlled-release packaging, which allows the release of targeted molecules into the environment around the food matrix ([Day, 2003](#); [Biji et al., 2015](#); [Panja et al., 2018](#); [Versino et al., 2023](#); [Ghosh et al., 2025b](#)). Various strategies, such as encapsulation, have been developed to control the release of active compounds, ensuring their effectiveness. Future research should focus on enhancing controlled-release kinetics to achieve a steady release of active substances throughout the food's shelf life.

1.4.2.2 Intelligent Packaging

Intelligent food packaging systems enable the real-time, non-invasive monitoring of safety and quality assessments, storage conditions, expiration dates, microbial growth, and freshness ([Panja et al., 2018](#)). This type of

packaging integrates various sensors, indicators, or QR codes into the packaging design ([Table 1.6](#)). Various types of sensors (biosensors, gas sensors, printed electronic sensors, chemical sensors), indicators (time-temperature indicators, chemical indicators, freshness indicators, seal and leak indicators, microwave doneness indicators, radio frequency identification indicators (RFID)), and electronic nose have been introduced for this purpose ([Biji et al., 2015](#); [Panja et al., 2018](#); [Palanisamy et al., 2024](#)). Smart packaging materials, which incorporate biosensors, can monitor various parameters such as pH levels, temperature, gas emissions, and production timeline of the product ([Upadhyay et al., 2024](#); [Eghbaljoo et al., 2025](#)).

1.5 CONSUMER PERCEPTION OF BIO-BASED PACKAGING

Understanding consumer intentions and behaviors toward sustainable packaging—particularly biomaterials—is essential for encouraging eco-conscious purchasing decisions. Consumers’ environmental attitudes, knowledge, and behavioral intentions can significantly affect their acceptance of eco-friendly packaging materials ([Shen et al., 2009](#)). In light of the urgent environmental challenges associated with the waste generated from conventional packaging and its extensive production scale, the shift toward sustainable biomaterials emerges not merely as an imperative but also as a strategic opportunity. Contemporary advancements in sustainable packaging endeavor to harmonize environmental objectives with consumer preferences, presenting alternatives that are both functional and environmentally conscious ([Duarte et al., 2024](#)). Nonetheless, in spite of the increasing cognizance of environmental hazards, particularly those arising from excessive plastic consumption, a significant number of consumers continue to prefer traditional packaging. This tendency is frequently

attributed to elevated costs and apprehensions regarding the durability or efficacy of sustainable biomaterials.

Within this framework, green perceived quality and green perceived value assume vital roles as determining factors. Green perceived quality pertains to the evaluation by consumers of a product's overall excellence in relation to its environmental characteristics, whereas green perceived value encompasses the perceived benefits that consumers believe they obtain in relation to the environmental repercussions. These two elements, alongside green satisfaction, significantly contribute to the establishment of green loyalty, which reflects a consumer's ongoing preference for sustainable offerings ([Pahlevi & Suhartanto, 2020](#)). Social influence and normative beliefs are very helpful in motivating consumers to opt for environmentally friendly packaging. When individuals observe their peers adopting sustainable behaviors, or when such actions are culturally sanctioned, they are more inclined to emulate those behaviors. The perceived effectiveness of the product and trust in the protective capabilities of sustainable packaging further reinforce affirmative attitudes and the proclivity to purchase ([Lan et al., 2023](#)). Price sensitivity remains an obstacle, indicating the necessity for competitive pricing or value-added strategies to rationalize cost differences. [Shimul and Cheah \(2023\)](#) further support the idea that consumers' ethical consciousness and sense of responsibility are positively associated with their intentions to engage with sustainable packaging initiatives. Based on these findings ([Duarte et al., 2024](#); [Pahlevi & Suhartanto, 2020](#); [Lan et al., 2023](#)), several strategic recommendations emerge to enhance consumer purchase intentions ([Figure 1.8](#)):

- Encouraging Environmental Awareness and Education: Initiatives aimed at education—such as workshops, campaigns, and clear labeling—are instrumental in aiding consumers in comprehending the environmental advantages of sustainable packaging, thereby empowering them to make informed choices.
- Addressing Practical Consumer Concerns: Brands are tasked with ensuring that sustainable packaging fulfills expectations pertaining to

quality, convenience, and cost to overcome hesitation and promote adoption.

- **Leveraging Social Influence:** The promotion of peer involvement and collaboration with green influencers can augment social validation and strengthen consumer trust in sustainable alternatives.
- **Aligning Marketing Strategies with Ethical Values:** Ethical branding and transparent communication that resonate with consumer values foster emotional connections and loyalty. Efforts in Corporate Social Responsibility (CSR) further substantiate the brand's commitment to sustainability.



FIGURE 1.8 Key strategies for enhancing consumer purchase intentions. [↗](#)

- **Government Role:** Legislative measures, incentives, and educational initiatives directed at both consumers and producers are essential in facilitating the swift adoption of sustainable packaging practices. In summary, stakeholders are encouraged to incorporate these insights into sustainable packaging strategies to enhance positive

environmental outcomes and enrich academic and managerial dialogues.

1.6 TESTING PROTOCOLS

A comprehensive understanding of the packaging materials is imperative for the development of packaging solutions that are specifically designed for certain food products. When employed for food packaging, these materials must adhere to specific regulatory standards to ensure the safety and quality of the packaged products. Various governmental and non-governmental bodies are responsible for establishing these standards. The array of standards utilized for the evaluation of packaging materials encompasses ASTM (American Society for Testing and Materials), ISO (International Organization for Standardization), the European Committee for Standardization, the International Safe Transit Association (ISTA), and the Technical Association of the Pulp and Paper Industry (TAPPI). Each type of packaging material exhibits unique characteristics with respect to its physical, chemical, thermal, mechanical, and biodegradability properties ([Ahmed, 2018](#); [Ghosh et al., 2025b](#); [Nizamuddin et al., 2024](#)). The analysis of these features is fundamental in predicting the efficacy of packaging materials when subjected to actual environmental conditions. Mechanical testing serves to assess the strength and durability of packaging materials under varying stress intensities. Thermal analysis is utilized to ascertain the behavior of packaging materials in response to temperature variations, thereby confirming their capability to endure diverse storage and transportation conditions. Chemical testing methodologies are employed to ensure that packaging materials do not lead to contamination or degradation of the internal product. Techniques of physical analysis are implemented to evaluate the intrinsic properties of sustainable packaging biomaterials, including their structural integrity, texture, and appearance. The food industry regards “optical transparency” as a significant parameter for

product identification. Nonetheless, light catalyzes oxidation in packaged food, which results in a decline in the quality of the packaged items. Consequently, packaging materials can mitigate photooxidation and the subsequent deterioration of food items, thereby providing superior light barrier properties. Biodegradability testing constitutes an essential component in the evaluation of the sustainability of packaging biomaterials. This testing aids in determining the extent to which a material decomposes naturally within the environment, particularly when subjected to microbial activity, moisture, and other environmental influences. Biodegradability assessment is crucial in ensuring that packaging materials composed of biopolymers (such as plant-based plastics or biodegradable plastics) do not contribute to the accumulation of long-term waste in the environment ([Ahmed, 2018](#); [Ghosh et al., 2025b](#); [Nizamuddin et al., 2024](#)). [Table 1.7](#) provides a guide for understanding the testing methodologies necessary for the development of sustainable packaging solutions. These test methods help manufacturers optimize the expected functionality attributes of designed biomaterials and meet sustainability requirements.

1.7 THE ANALYSIS OF GLOBAL MARKET

[Figure 1.9](#) shows the distribution of sustainable biomaterials across various industrial sectors ([Jain et al., 2024](#)). The pharmaceutical industry comprises 6% of the overall distribution, employing biomaterials in packaging and delivery systems. The biotechnology sector contributes 15%, driven by the application of biomaterials in biofuels, biopharmaceuticals, and biodegradable products. The food sector accounts for 13% of the utilization of environmentally friendly additives and packaging solutions. Biodegradable substances and bioplastics represent 15% of packaging applications, whereas medical devices and implants constitute 14%. The agricultural sector employs 9% of biomaterials for mulch and fertilizers, while the textile industry uses 8% for substances such as hemp and organic

cotton. Lastly, the manufacturing industry, which encompasses automotive and construction materials, accounts for 16% of the total utilization. According to GlobeNewswire, the global food packaging sector was appraised at approximately US\$358 billion in 2022, with an anticipated market valuation of US\$592.8 billion by 2030 ([Upadhyay et al., 2024](#)), as depicted in [Figure 1.9](#).

TABLE 1.7 Existing Standard Methods for the Analysis of Sustainable Packaging Biomaterial [↗](#)

<i>FEATURE</i>	<i>PARAMETER</i>	<i>STANDARD METHOD/GUIDELINE</i>
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<i>FEATURE</i>	<i>PARAMETER</i>	<i>STANDARD METHOD/GUIDELINE</i>
Mechanical analysis	Compression test	ISO 604:2002, ASTM d695–15, ASTM D6641/D6641M-16e1, ASTM D3410/D3410M -1
	Tensile test	ISO 527–1:2012, ASTM D1708-13, ASTM D638–14, ASTM D882, ASTM D3039
	Vibration test	ISO 8318:2000, ASTM D3580—95 (2015), ISO 2247:2000; ASTM D999—08(2015)
	Drop test	ISO 2248:1985; ASTM D5276—98(2017)
	Impact test	ISO 2248, ISO 13355:2016; ASTM D880, ISO 2244:2000, ASTM D4003, ASTM D5277
	Heat seal integrity	ASTM F88/F88M, ASTM F1921/F1921M—12e1, ASTM F2391—05 (2016); ASTM F1886/F1886M–16

<i>FEATURE</i>	<i>PARAMETER</i>	<i>STANDARD METHOD/GUIDELINE</i>
Physical analysis	Thickness measurement	ASTM F2251–13 2013
	Gloss detection	ASTM D2457, ASTM D523
	Leak testing	ASTM F2096—11, ASTM F3039—15, ASTM D3078—02 (2013), ASTM F2338—09 (2013), ASTM D4991—07 (2015), ASTM F3169—16 Measurement
	Water vapor transmission rate	Gravimetric method , ASTM E96, ASTM D1653; ISO 2528
		Modulated infrared sensor ASTM F1249, ISO 15106–2, F1249—13, ASTM F372, ASTM
		Relative humidity sensor ASTM E398; ISO 15106–1–Part 1
	Gas permeability testing	ASTM F1927-14, ASTM F1307-14, ASTM D3985—05(2010)e1
Thermal analysis	Differential scanning calorimetry	ASTM E2602 -09 (2015), ASTM D3418–15, ASTM D6604- 00 (2013), ISO 11357–2-Part 2, ISO 11357–3
	Thermogravimetric analysis	ASTM E1356—08 (2014)
	Thermomechanical analysis	Ahmed (2018)
Chemical analysis	Testing of migration from packaging material	Ahmed (2018)
Optical properties	Refractometric method, microscopic method,	Ghosh et al. (2025b)

<i>FEATURE</i>	<i>PARAMETER</i>	<i>STANDARD METHOD/GUIDELINE</i>
	luminous transmittance and haze, and color	
Biodegradability testing	-Soil burial method -Microbiological Degradation test -Compost method -Enzymatic degradation test	ISO 14851:1999, ISO 14853, ASTM D6868—17, ASTM G21—15

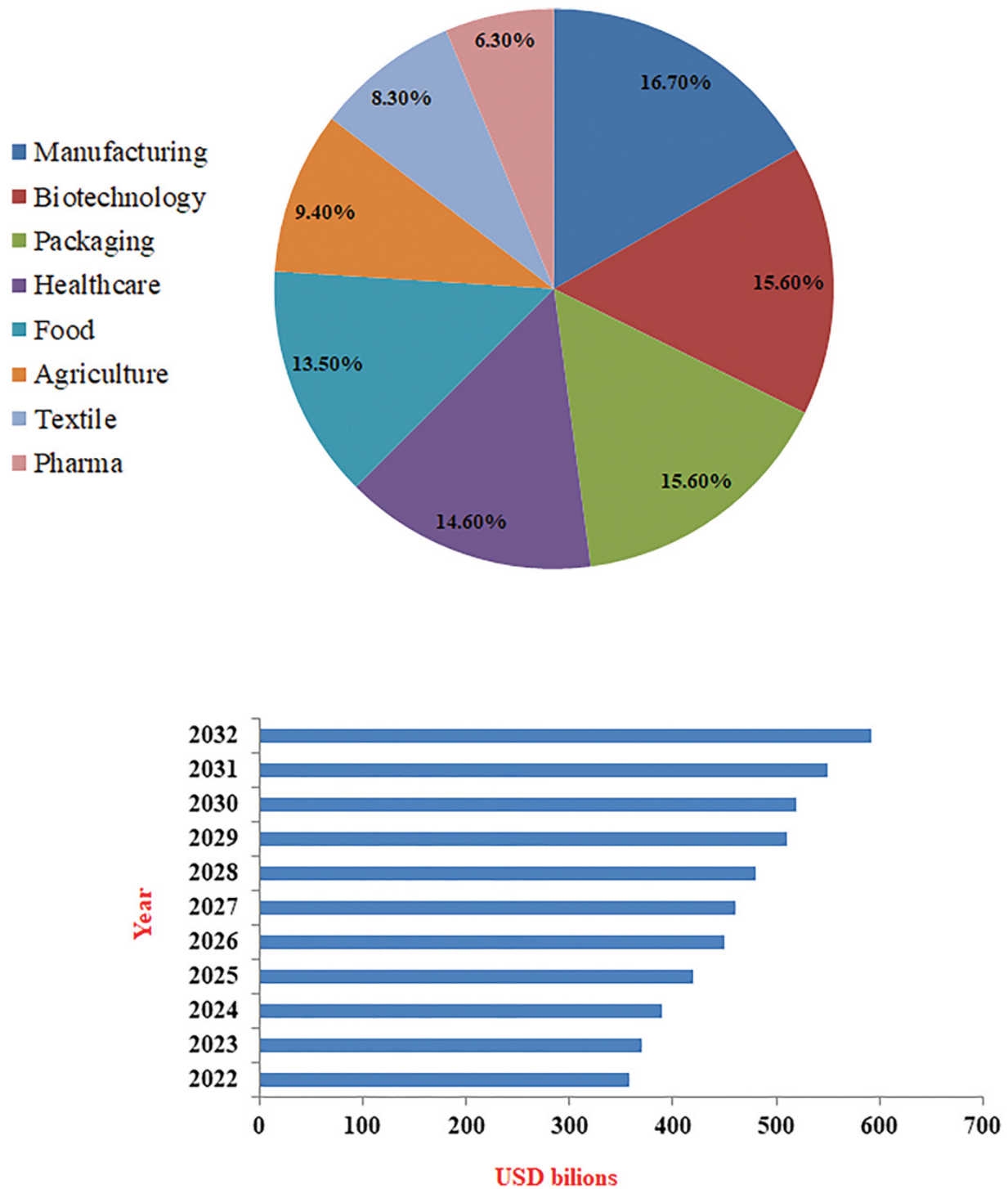


FIGURE 1.9 Distribution of sustainable biomaterial across various sectors and the projected expansion of the global food packaging market from 2022 to 2032. [↗](#)

The market for eco-friendly food packaging was valued at US\$199.7 billion in 2024 and is projected to expand at a compound annual growth rate

(CAGR) of 6.6%, reaching an estimated valuation of US\$407.5 billion by 2034. The market is segmented based on product type into containers, bags, cartons and boxes, jars and bottles, and others. Among these, the containers segment is expected to experience significant growth, with a projected CAGR of over 8%, reaching a value exceeding US\$133 billion by 2034. Among the world's continents, North America led the market in 2024, holding a dominant share of over 45%. Key players in the eco-friendly food packaging industry include Amcor, Biomass Packaging, Biopak, Eco-Products, Genpak, International Paper, Karl Knauer, Mondi, Mpacks, Nordic Paper, PacknWood, Pappco Greenware, Sealed Air, Smurfit Kappa, Sonoco Products, Stora Enso, Tetra Pak, TIPA, Vegware, and WestRock. (Source: [Eco-friendly Food Packaging Market, Global Forecast, 2025–2034](#)).

1.8 REGULATORY REQUIREMENTS IN THE COMMERCIALIZATION OF SUSTAINABLE PACKAGING

Due to the escalating environmental issues associated with single-use and non-biodegradable plastics, the establishment of regulations on sustainable food packaging has attracted increasing attention worldwide. To guarantee the safety and quality of foods packaged with sustainable biomaterials, legislative and regulatory bodies need to establish clear requirements for the commercial applications of these packaging materials.

However, the regulatory environment surrounding sustainable food packaging is complex and varies significantly across regions. Governments are progressively introducing mandates aimed at reducing plastic waste, regulating packaging disposal, and encouraging the use of recyclable, compostable, or biodegradable materials ([Amin et al., 2021](#); [Thapliyal et al., 2024](#)).

Numerous countries ([Figure 1.10](#)) have already established regulations that advocate for more environmentally sustainable packaging alternatives, frequently aligned with local and national cultural contexts. [Table 1.8](#) provides a detailed overview of the diverse regulatory frameworks governing sustainable food packaging materials across various nations, illuminating their distinctive approaches to environmental conservation. These countries exhibit their dedication to sustainability through various regulatory measures, including bans on single-use plastics, recyclability standards, and extended producer responsibility (EPR) initiatives ([Filho et al., 2019](#); [Thapliyal et al., 2024](#)). Navigating this evolving regulatory landscape necessitates that companies remain vigilant regarding legal developments, engage in collaborative efforts with material suppliers, and adapt to regional differences. Failure to comply with these regulations can result in financial repercussions or restricted market access.



FIGURE 1.10 Different countries involved in the development of sustainable food packaging regulations ([Thapliyal et al., 2024](#)). ↵

TABLE 1.8 Regulations Related to Sustainable Food Packaging in Different Countries ([Thapliyal et al., 2024](#)) 

<i>COUNTRY</i>	<i>BANNING THE USE OF SINGLE- USE PLASTICS</i>	<i>SUSTAINABLE FOOD PACKAGING REQUIREMENTS</i>	<i>EPR*</i>
India	Banning the use of some single-use plastics	Food Safety and Packaging Regulations (2022) and Standards	Plastic Waste Management (PWM) Rules (2016)
EU	The directive to ban some single-use plastics came into effect in July 2021	(1) Commission Regulation (EU) No 10/2011 of 14 January 2011 (2) Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004	European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste
China	Single-use plastic bag bans in some regions suggested a nationwide ban on plastic bags, straws, and non-degradable cutlery by 2025	GB 4806.6–2016	Solid Waste Pollution Prevention and Control Law (2005)
Japan	There is no nationwide ban	Food Sanitation Act	The Containers and Packaging Recycling Law (CPRL) (2000)
USA	There is no nationwide ban	Guide to using recycled plastics	The United States of America has no

<i>COUNTRY</i>	<i>BANNING THE USE OF SINGLE- USE PLASTICS</i>	<i>SUSTAINABLE FOOD PACKAGING REQUIREMENTS</i>	<i>EPR*</i>
			federal EPR regulations, but some states do
South Korea	A ban on plastic bags and single-use plastic cups, straws, and cutlery by 2027 has been proposed	Raw material recycling standard for food containers	According to the Resource Recycling Act
UK	Banning cotton buds, single-use plastic straws, and stirrers since October 2020; banning polystyrene, plastic cutlery, and plates by 2023	Regulations of manufacturer responsibilities (Packaging Waste, 2007)	Packaging Waste Regulations in 2007, its amendment in 2015
Australia	Banning plastic straws, stirrers, cutlery, and single-use plastic bags in several regions, suggested by 2025	There are no specific requirements, but guidelines are available	The National Environment Protection (applied Packaging Materials)

** Extended Producer Responsibility (EPR) is an environmental policy approach that extends a producer's responsibility beyond the point of sale to include the post-consumer stage of a product's life cycle. It is regarded as one of the fundamental tools within the framework of waste management policy, promoting the enforcement of the European waste hierarchy.*

TABLE 1.9 A SWOT Analysis of Sustainable Biomaterials in the Food Packaging Industry 

<i>FACTORS</i>	<i>POSITIVE</i>	<i>NEGATIVE</i>
	Strengths	Weaknesses
Internal	(1) Environmental benefits Renewable, biodegradable, compostable (2) Consumer demand for eco-friendly packaging Increasing consumer awareness and their preference for eco-friendly products (3) Regulatory support and incentives Many countries have imposed stricter regulations on plastic waste and are encouraging the use of biodegradable packaging (4) Brand differentiation Companies that switch to sustainable packaging can improve their brand image and consumer loyalty (5) Waste reduction Sustainable biomaterials are renewable, which can help decrease food waste and promote a circular economy	(1) Higher production costs Sustainable biomaterials are often more expensive to produce than conventional plastics, leading to higher packaging costs for manufacturers (2) Performance limitations and durability Some sustainable biomaterials may not meet the performance standards due to shorter shelf life, less durability, and decreased moisture resistance (3) Limited scalability The production of certain sustainable biomaterials may not yet be scalable enough to meet the global demand for food packaging, especially if they depend on specific raw materials (4) Supply chain constraints Relying on agricultural products for the production of sustainable biomaterials may cause supply chain disruptions, specifically with

<i>FACTORS</i>	<i>POSITIVE</i>	<i>NEGATIVE</i>
		seasonal crops or in the face of climate change
	Opportunities	Threats
External	(1) Growing market demand With increasing environmental concerns, more industries are looking for sustainable biomaterials (2) Innovation in materials and the emergence of new technology The use of nanotechnology and smart technology for the development of new sustainable biomaterials (3) Partnerships and collaborations: Collaborations between food manufacturers, packaging companies, and universities can develop more efficient, scalable, and cost-effective sustainable packaging biomaterials, leading to technological innovations and economies of scale (4) Circular economy integration The focus on the circular economy provides an opportunity to integrate sustainable packaging into a closed-loop system where	(1) Competition from traditional materials petroleum-based packaging materials (plastics) still dominate the market due to their lower cost compared to sustainable biomaterials and established supply chains (2) Technological and production challenges There are challenges in scaling up the manufacturing of sustainable biomaterials, guaranteeing durability, and meeting the various needs of the industries (3) Market fragmentation The packaging market for sustainable biomaterials packaging is fragmented, with different materials and the emergence of new technologies, which makes it difficult for companies to navigate and select the best possible option (4) Consumer perception of durability

<i>FACTORS</i>	<i>POSITIVE</i>	<i>NEGATIVE</i>
	packaging is reused, recycled, or composted, resulting in waste reduction and sustainability promotion	Some consumers may perceive sustainable packaging as less durable or less effective in preserving food products, leading to a barrier to acceptance (5) Economic downturns Businesses may prioritize cost savings over environmental concerns, making them less inclined to invest in sustainable solutions

1.9 FUTURE TRENDS

The design and development of sustainable food packaging will be accompanied by the introduction of smart labels and innovation in the composition of biopolymers. This can result in sustainable and eco-friendly packaging solutions. The application of nano- and smart packaging methodologies, particularly in conjunction with Artificial Intelligence (AI) systems, presents significant opportunities for optimizing production methodologies and enhancing the performance of packaging materials. For instance, AI can facilitate the prediction of material behaviors, improve manufacturing efficiency, and guarantee superior quality assurance. Nevertheless, as these technological innovations progress, a pivotal consideration will be the assurance of their safety. Due to the migration of substances from biopolymer packaging into the food matrix, safety monitoring is required to control any potential hazards to consumer health. Testing protocols, including the evaluations of cytotoxicity,

biodegradability, and long-term environmental impact, will be necessary to ensure that these novel materials do not cause unwanted harm to consumers. Furthermore, in an increasingly interconnected global marketplace, the establishment of robust testing protocols and the harmonization of international standards will be imperative.

All stakeholders, including industry players, research institutions, and governmental bodies, must engage in close collaboration to ensure that sustainable materials are not only safe and effective but also align with existing food safety regulations. Ultimately, the extensive acceptance of sustainable food packaging will be contingent upon a balanced approach that gives precedence to both food safety and sustainable development.

1.10 CONCLUSION

Over the years, petroleum-based packaging materials have predominated in the food packaging sector. However, the extensive utilization of these synthetic polymers has caused considerable environmental challenges, particularly in relation to the pollution associated with plastic waste. In response to the increasing concerns over the environmental consequences of petroleum-derived plastics, sustainable biomaterials for food packaging, such as biopolymer-derived films and coatings, present a promising alternative. However, the selection of appropriate bio-based materials must be according to the specific storage conditions required for different food types. Biomaterials help minimize landfill waste and reduce the carbon footprint of food packaging. These materials are favored for their biodegradability, eco-friendliness, renewability, non-toxicity, and lightweight properties. Despite their advantages, several challenges remain, including limited performance (weak thermal, mechanical, strength, and barrier properties), high production costs, and supply chain constraints. These issues can hinder the widespread adoption and commercialization of sustainable biomaterials. The transition to biomaterials for sustainable food

packaging presents both threats/opportunities and weaknesses/strengths, as detailed in the SWOT analysis ([Table 1.9](#)).

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Nanotechnology in Food Packaging

2

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2.1 INTRODUCTION

Foodborne diseases caused by microbial agents such as bacteria, fungi, and viruses are causing serious food safety concerns worldwide due to the alarming risks of food contamination and related diseases ([Emamhadi et al., 2020](#)). Food packaging materials are widely acknowledged for their critical role in preserving edible consumables while ensuring their quality during transit, storage, and handling ([del Rosario Herrera-Rivera et al., 2024](#); [Kaur et al., 2024a](#)). Acting as a barrier to different physical, chemical, and biological external factors, food packaging enables healthy and reliable ways to deliver food to consumers. Over the years, there has been a significant advancement in the materials utilized for food packaging, starting from clay containers, polymers, biopolymers, and now nanotechnology-based materials. For the development of efficient and innovative packaging, nanoscale materials have been actively explored for their desirable properties, including improved mechanical strength,

antimicrobial characteristics, and enhanced moisture and gas barrier properties ([de Sousa et al., 2023](#)). These promising features of nano-based materials are a consequence of their larger surface area to volume ratio and higher mass transfer rate in comparison to the macro-sized particles ([Kaur et al., 2024b](#)).

Nanomaterials are being incorporated in polymer matrices that are used for the production of novel bio-nanocomposites and other nanostructured products for various implementations in the food sector, including packed food components, preservatives, wrapping materials, antimicrobial sensors ([Singh et al., 2023](#)). With an aim to enhance the freshness, food quality, shelf life, and safety of the consumables, several nanomaterials, including metal nanoparticles, nanoclays, and nanoemulsions, are being tested for their potential to be utilized as packaging materials ([Agarwal et al., 2020](#)). Engineered nanoparticles, called manufactured nanomaterials, such as zinc oxide, titanium dioxide, silicon dioxide, transition metals (silver, iron, etc.), as well as alkaline earth metals (magnesium, calcium, etc.), have been employed as packaging components in the food and beverage sector ([Enescu et al., 2019](#)). Advancements in smart and active packaging have been witnessed, involving the use of nanosensors and nano-biosensors that can detect spoilage, contaminants, or changes in food quality in real-time. Materials like carbon nanotubes and silicon dioxide are utilized to develop sensors that monitor gases released during spoilage, such as ammonia or sulfur compounds, thereby providing immediate feedback on food freshness and reducing food waste ([Chausali et al., 2022](#); [Jana & Dev, 2022](#); [Jayakumar et al., 2022](#)). Additionally, optoelectronic nanomaterials, including quantum dots, are being developed for intelligent packaging systems that visually indicate the condition of the food product ([Babu, 2022](#)).

Since the role of nanotechnology is significantly affecting the food industry, widening the range of options for formulation and production of nanomaterial-based functional products is imperative. Further, with the current studies directed at improving composition, processing, and packaging using nano-based matrices, knowledge about particle migration

and toxicity imparted by these materials in food products remains limited. Therefore, this chapter focuses on the advancements, opportunities, and challenges presented by the use of nanotechnology in the area of food processing, food security, and food packaging. This exploration ascertains the utilization of nanoscale materials in transforming the landscape of the food packaging industry while exploring the practicality of newer cutting-edge approaches to provide sustainable and eco-friendly solutions in the present-day scenario.

2.2 NANOMATERIALS: STRUCTURAL FEATURES AND PROPERTIES

Nanomaterials are materials with at least one dimension in the range of 1–100 nm. The materials with three, two, and one dimensions in the nanoscale are termed nanoparticles, nanowires, and nanofilms, respectively ([Figure 2.1](#)). The primary features of nanomaterials are their size, shape, and composition, which can be tuned to modify their properties ([Hong, 2019](#)).

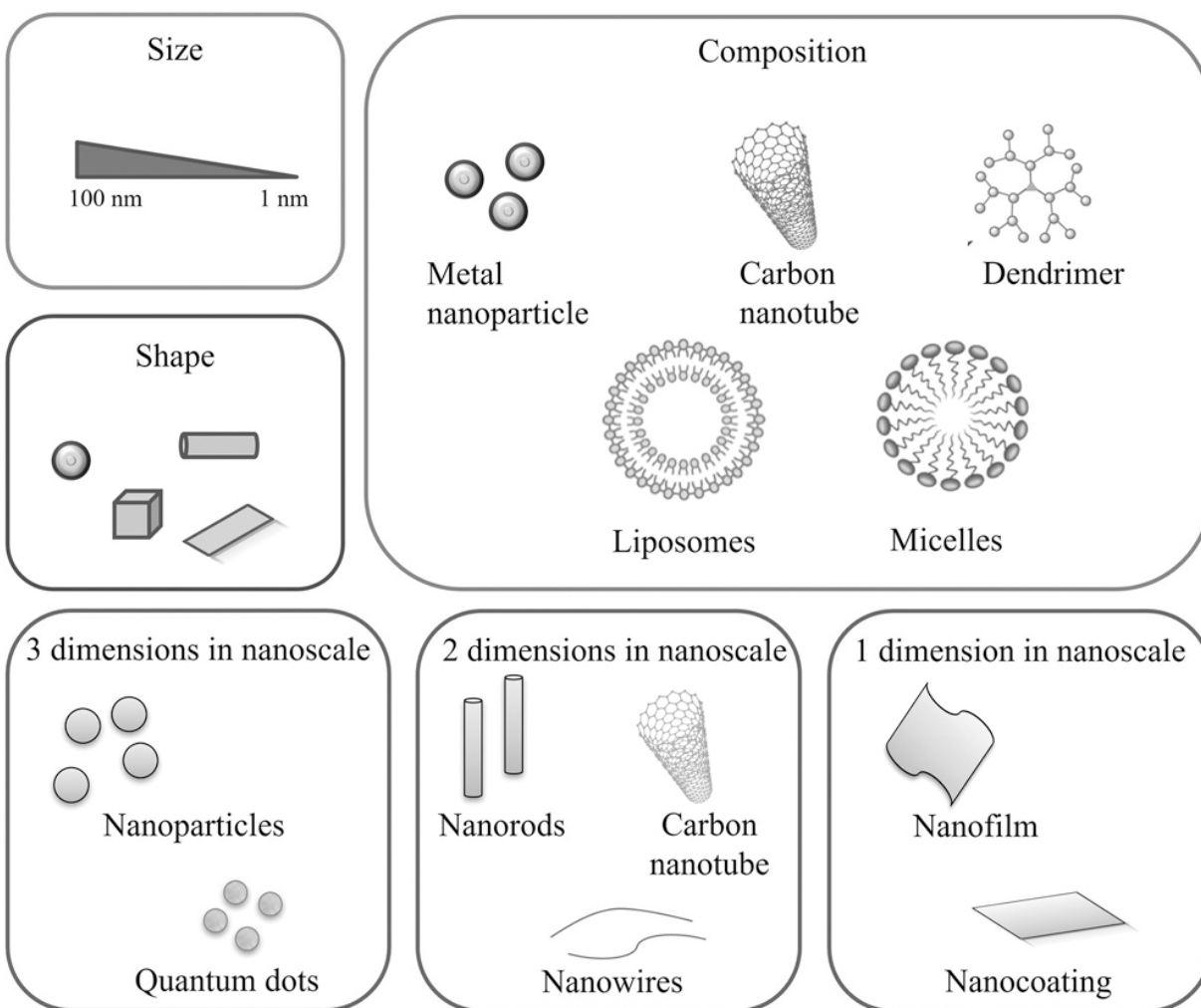


FIGURE 2.1 Physical features of nanomaterials along with suitable instances. [↗](#)

The nanomaterials possess a significantly higher ratio of surface area per unit volume and enhanced chemical reactivity in comparison to bulk materials ([Kaur et al., 2023](#); [Tomar et al., 2020](#)). Their mechanical properties are also notably superior, owing to improved crystal perfection or reduced crystallographic defects ([Agarwal et al., 2020](#)). These materials demonstrate remarkable mechanical properties not found in their macroscopic forms ([Wu et al., 2020](#)). Depending on their specific nature, nanomaterials can also exhibit exceptional thermal conductivity at the nanoscale, which is often much greater than that of bulk materials ([Krishnan et al., 2019](#)). Hence, incorporating nanomaterials into compatible polymer matrices can provide increased mechanical strength and heat

resistance to the synthesized nanocomposites and, as such, be suitable for packaging applications ([Arvanitoyannis & Bosnea, 2001](#)). For instance, integrating carbon nanotubes (CNTs) or nanoclay into conventional thermoplastics disperses them throughout the polymer matrix, which modifies molecular mobility and polymer relaxation. As a result, the mechanical and thermal qualities of the matrix are greatly enhanced.

Furthermore, some nanomaterials possess excellent antimicrobial and antioxidative properties, offering cutting-edge solutions for food packaging ([Handford et al., 2014](#); [Silvestre et al., 2011](#)). Nanoparticles can penetrate the microbial cell walls and biofilm layers, which can cause severe destruction of the DNA ([Yilmaz et al., 2023](#)). Therefore, the use of nanomaterials to improve food packaging is becoming popular, especially for active antimicrobial packaging ([Becerril et al., 2020](#)). For instance, the incorporation of gold nanoparticles into poly(vinyl) alcohol composite films resulted in antibacterial activity against *Escherichia coli* with a 13 mm inhibition zone, compared to an initial 10 mm ([Chowdhury et al., 2020](#)). Similarly, [Zhai et al. \(2022\)](#) prepared a starch/poly (butylene adipate-co-terephthalate) nanocomposite film with the incorporation of zinc oxide and silver nanoparticles using an extrusion-blowing technique. The synthesized films showed inhibitory action against *Streptococcus aureus* and *E. coli*, thereby inhibiting rot and maintaining freshness in nectarines and peaches packaged in these films. Various nanomaterials, such as silver nanoparticles (AgNPs) ([de Moura et al., 2012](#)), nanoclay ([Bumbudsanpharoke & Ko, 2019](#)), nano zinc oxide ([Sanuja et al., 2015](#)), nanotitanium dioxide ([El-Wakil et al., 2015](#)), carbon nanotubes ([Pattanshetti et al., 2020](#)), cellulose nanowhiskers ([Haghighi et al., 2021](#)), and starch nanocrystals ([Martins et al., 2022](#)) have been incorporated into food packaging to provide specific functional benefits. Every nanomaterial imparts unique characteristics to the packaging material, creating a range of functional applications ([Rubilar et al., 2014](#)).

The interfacial features of nanomaterials can be modified using chemical agents such as surfactants ([Heinz et al., 2017](#)). The nanoparticle-nanoparticle or nanoparticle-fluid interactions may be attractive or repulsive

in nature, as a result of which the agglomeration or aggregation of nanoparticles may occur. The methods for preparing nanocomposite polymer packaging films must ensure effective dispersion of nanofiller into the matrix to achieve intercalated or exfoliated structures ([de Oliveira & Beatrice, 2018](#)). This dispersion can be affected by surface modification of nanoparticles. Further, the incorporation of nanoparticles into bio-nanocomposite materials enhances their barrier and mechanical characteristics, such as elasticity, stability over a variety of temperature and moisture levels, and gas exposure (against O₂, CO₂, etc.) ([Youssef & El-Sayed, 2018](#)).

2.3 DIFFERENT TYPES OF NANOMATERIALS IN FOOD PACKAGING

Nanomaterials used in food packaging are available in different forms, each providing distinct properties and advantages ([Table 2.1](#)). Some of the most common types of nanomaterials utilized in the industries are described next.

TABLE 2.1 Different Types of Nanomaterials Utilized in Food Packaging, along with Their Properties and Applications [↗](#)

NANOMATERIALS	PROPERTIES	APPLICATIONS	REFERENCES
Nanoclays	Layered mineral silicates modified at the nanoscale exhibit enhanced barrier properties and increased strength	Barrier films to block gases, moisture, and UV light	Chaudhary et al. (2020) , Nath et al. (2022) , Deshmukh et al. (2023) , Gmoshinski et al. (2020)

<i>NANOMATERIALS</i>	<i>PROPERTIES</i>	<i>APPLICATIONS</i>	<i>REFERENCES</i>
Silver Nanoparticles	Nanoscale silver particles with antimicrobial properties that inhibit bacterial growth	Antimicrobial packaging for meats, fruits, and vegetables	Kraśniewska et al. (2020) , Simbine et al. (2019) , Kumar et al. (2021) , Biswal and Misra (2020)
Titanium Dioxide Nanoparticles	Photocatalytic and antimicrobial properties, offering UV protection and microbial inhibition	Coatings to prevent microbial contamination and UV damage	Zhang and Rhim (2022) , Sani et al. (2022) , Jayakumar et al. (2022) , Mesgari et al. (2021)
Zinc Oxide Nanoparticles	Zinc oxide at the nanoscale possesses antimicrobial and UV-blocking capabilities	Packaging to inhibit microbial growth and protect against UV	Zhang et al. (2023) , Zare et al. (2022) , Smaoui et al. (2023) , Channa et al. (2022)
Nanocellulose	Nano-sized cellulose fibers from plant materials that are renewable, biodegradable, with enhanced strength	Reinforcement for biodegradable packaging materials	Ahankari et al. (2021) , Vilarinho et al. (2018b) , Fotie et al. (2020) , Criado et al. (2018) , Zhang et al. (2021) , Silva et al. (2020)
Carbon Nanotubes	Cylindrical structures with a high strength-to-	Reinforcement and smart	Wen et al. (2022) , Sivakumar and Hema (2024) ,

<i>NANOMATERIALS</i>	<i>PROPERTIES</i>	<i>APPLICATIONS</i>	<i>REFERENCES</i>
	weight ratio and conductivity	packaging applications	Mitura et al. (2021)
Biopolymer Nanoparticles	Nanoparticles from biopolymers like chitosan and PLA that are biodegradable and enhance mechanical properties	Biodegradable and sustainable packaging solutions	Taherimehr et al. (2021) , Khezerlou et al. (2021) , Nasrollahzadeh et al. (2021) , Priyadarshi et al. (2022)
Silica Nanoparticles	Nanoscale silica is used in coatings to improve durability and reduce permeability	Coatings for enhanced mechanical and barrier properties	Dong et al. (2022) , Lin et al. (2023) , Wu et al. (2019) , Mukherjee et al. (2023)

2.3.1 Nanoclays

The first nanomaterial to make a significant impact in the market of polymer nanocomposites, and the one that is the most commonly used in food packaging, is nanoclay. Specifically, montmorillonite (MMT) comprises an octahedral aluminum hydroxide sheet positioned between two layers of tetrahedral silica, forming a layered structure ([Kausar, 2020](#)). Due to its large surface area, excellent cation exchange capacity, and favorable swelling properties, MMT is extensively used to enhance the physical properties of plastic packaging ([Bangar et al., 2023](#)). It is particularly effective at improving barriers to gases and moisture, helping to preserve

food quality by reducing permeability ([Giannakas & Leontiou, 2018](#)). MMT, derived from volcanic ash and rocks, is readily available and cost-effective, making it an attractive option for large-scale applications. MMT often comes in platelet clusters in polymer composites, requiring high shear or sonication techniques to disperse it uniformly within the polymer matrix for optimal performance. This widespread use in food packaging highlights MMT's importance in advancing the industry's efforts to enhance product protection and extend shelf life. The application of nanoclay to food packaging began in the 1990s. One example of commercial nanoclay composites is Durethan® KU2-2601, the trade name of a nanoclay-engineered polyamide film developed by Bayer and commercialized under Lanxess Deutschland. It is used in a variety of applications, including medical and food packaging films. Durethan® KU2-2601 is comprised of clay platelets distributed throughout the polymer matrix that act as a barrier. Due to its superior characteristics, it is extensively used for beverage packaging as well ([Chaudhary et al., 2020](#)).

2.3.2 Silver Nanoparticles

Silver (Ag) has long been employed as an antimicrobial agent to preserve food and beverages ([Yang et al., 2021](#)). Silver nanoparticles (AgNPs) are usually metallic silver intended for sterilization and possess antimicrobial, anti-yeast, anti-fungal, and antiviral activities as they have a larger surface area per mass compared to micro-scale silver particles or bulk silver content ([Chaudhary et al., 2020](#)). Additionally, AgNPs can bind to the surface of the cell and degrade lipo-polysaccharides, thus forming a pit within the cell membrane. AgNPs can be integrated into plastic polymers for packaging using several different methods. For example, silver ions can be deposited or trapped in the porous zeolite, and these materials can then be applied to plastics. It has been reported that AgNPs and ZnO-NPs containing low-density polyethylene (LDPE) can preserve and prolong the shelf life of orange juice ([del Rosario Herrera-Rivera et al., 2024](#)). This active nanocomposite is highly effective as an antimicrobial nanomaterial in

combination with heat treatment. These can be incorporated into packaging to provide antimicrobial protection for perishable products such as meats, fruits, and vegetables. This not only enhances food safety by reducing the risk of foodborne pathogens but also extends the shelf life of these products.

2.3.3 Titanium Dioxide Nanoparticles

Titanium dioxide nanoparticles (TiO₂-NPs) are some of the most widely studied nanomaterials in food packaging because of their beneficial properties, such as thermal stability, chemical inertness, and affordability. Authorized by the United States Food and Drug Administration (USFDA) in 1996 for use as a food additive and in materials that come into contact with food, TiO₂-NPs have since become widely used for their photocatalytic and antimicrobial capabilities ([Berardinelli & Parisi, 2021](#)). When exposed to UV light, TiO₂-NPs generate reactive oxygen species, such as superoxide anions and hydroxyl radicals, which damage microbial cell walls, resulting in a potent antimicrobial effect. This makes them highly effective in preventing microbial contamination in food packaging. Additionally, TiO₂-NPs are commonly applied as UV blockers to protect food from degradation, particularly in products sensitive to light, such as dairy ([Wasilewska et al., 2023](#)). Their ability to modify biodegradable films enhances the durability and functionality of eco-friendly packaging solutions. TiO₂ also serves as a pigment, imparting whiteness and brightness to packaging materials, improving their aesthetic appeal. Its non-toxic, non-flammable, and non-volatile nature further ensures food safety ([Chaudhary et al., 2020](#)).

2.3.4 Zinc Oxide Nanoparticles

Zinc oxide nanoparticles (ZnO-NPs) are recognized for their diverse morphologies and robust antimicrobial properties, demonstrating significant inhibition against a wide range of bacterial species, including *E. coli*, *Bacillus atrophaeus*, and *Salmonella aureus* ([Mendes et al., 2022](#)). ZnO-NPs are particularly appealing for packaging purposes due to their

affordability and lower toxicity compared to silver nanoparticles (AgNPs), making them safer for both humans and animals ([Kim et al., 2022](#)). Under UV irradiation, ZnO can generate substantial amounts of hydrogen peroxide, which induces oxidative stress in bacterial cells, enhancing its antimicrobial effect. Studies have shown that zinc ions play a crucial role in exhibiting bacteriostatic properties, inhibiting bacterial growth without necessarily destroying the cells. For instance, packaging films composed of polylactic acid (PLA) infused with ZnO-NPs have demonstrated improved mechanical and antimicrobial properties ([Dejene & Gudayu, 2024](#)). Additionally, ZnO-NPs have shown effectiveness in preserving food products, such as ready-to-eat poultry, by protecting against bacterial contamination ([Souza et al., 2020](#)). Research indicates that these nanoparticles can also extend the shelf life of fresh produce, such as cut apples, by reducing spoilage-related factors like malondialdehyde (MDA) and ethylene levels under UV light exposure. Overall, ZnO-NPs contribute significantly to enhancing food safety and prolonging shelf life by preventing spoilage through their antimicrobial and UV-blocking properties ([Gao et al., 2024](#)).

2.3.5 Nanocellulose

Nanocellulose, also known as cellulose nanofibers, microfibrils, or cellulose nanowhiskers, consists of alternating crystalline and amorphous regions. The crystalline region creates a strong network of hydrogen bonds, giving cellulose high axial stiffness, which makes it an excellent reinforcement material for composite fillers ([Ganapathy et al., 2023](#)). Due to its high aspect ratio, even a small quantity of nanocellulose greatly improves the strength and rigidity of polymers, rendering them more effective than traditional fillers. Nanocellulose can be extracted from a variety of plant sources. For example, cellulose nanowhiskers have been obtained from coconut husk fibers via hydrolysis, and bamboo fibers have been incorporated into soy protein-based composites to enhance mechanical properties like Young's modulus and fracture stress ([Sanga Pachuaui, 2015](#)).

These qualities, combined with its excellent biodegradability and renewable nature, make nanocellulose a promising alternative to traditional petroleum-based materials in the development of stronger, lightweight, and eco-friendly biodegradable packaging.

2.3.6 Carbon Nanotubes

Carbon nanotubes (CNTs), cylindrical structures with exceptional electrical conductivity and mechanical strength, have recently been incorporated into polymers such as polyvinyl alcohol (PVOH), polypropylene (PP), nylon, and polylactic acid (PLA) for packaging applications ([Idumah et al., 2020](#)). CNTs come in two main forms: single-walled (SWCNTs), which consist of a single-atom-thick layer of carbon, and multi-walled (MWCNTs), which have several concentric layers. Both types provide an extraordinarily high elastic modulus and tensile strength when added to polymer matrices, significantly enhancing the mechanical properties of packaging materials ([Onyancha et al., 2022](#)). CNTs also exhibit antimicrobial properties; for instance, bacteria like *E. coli* are highly sensitive to pure SWCNTs. Additionally, CNTs are being explored for use in intelligent packaging systems. For example, researchers at Technische Universität München have developed CNT-based gas sensors that can be sprayed onto packaging films to create a transparent, wireless sensor system. This smart packaging can detect changes in gas composition, signaling when food is close to spoiling ([Kumari et al., 2024](#)). The ability of CNTs to integrate electronic components into packaging materials, combined with their high strength-to-weight ratio, makes them a promising innovation for future food packaging solutions, especially in enhancing product safety and shelf life.

2.3.7 Nanoparticles of Biopolymers

Nanoparticles of biopolymers have emerged as eco-friendly alternatives to petroleum-based polymers for packaging applications. These biopolymers, derived from renewable resources, include polysaccharides like starch, cellulose derivatives, chitosan, and alginates, as well as proteins such as

casein, whey, and gluten, and polymers like polylactic acid (PLA), polyhydroxybutyrates (PHB), and polycaprolactone (PCL) ([Ali et al., 2023](#)). Nanoparticles of these biopolymers are used to improve the mechanical strength and barrier properties, such as resistance to oxygen and moisture, of packaging materials. However, challenges such as high molecular weight, viscosity, and fragility can hinder their large-scale use ([Kaur et al., 2023](#); [Chaudhary et al., 2020](#)). To overcome these limitations, biopolymers are often combined with other materials, plasticizers, or compatibilizers to enhance their performance. Additionally, surface modifications, physical cross-linking, and grafting techniques can further improve their functionality for packaging applications ([Khezerlou et al., 2021](#)). These biodegradable nanoparticle-based materials are environmentally friendly and sustainable, offering a promising solution for reducing plastic waste while providing reliable packaging performance.

2.3.8 Silica Nanoparticles

Nano-silica is widely used in food packaging, particularly for creating hydrophobic coatings that offer self-cleaning properties ([Zhang et al., 2023a](#)). When applied, these non-adhesive coatings allow food to move freely within containers or jars, preventing waste and making it easier to pour or remove food products. This technology is especially beneficial for items like beer, wine, and powdered soups, where maintaining product quality and flow is critical ([Dubey et al., 2023](#)). For instance, coatings made from Aerosil® silica nanoparticles can create super-hydrophobic surfaces, like on paperboard, mimicking the lotus effect, which provides excellent water resistance. This results in packaging materials that are not only durable but also highly resistant to moisture ([Parvate et al., 2020](#)). By enhancing the mechanical strength and reducing the permeability to gases and moisture, nano-silica coatings extend the shelf life of food products and offer better protection against environmental factors, making them a valuable innovation in modern food packaging.

2.4 METHODS FOR THE FABRICATION OF NANO-BASED PACKAGING

Nanocomposite packaging is primarily formed by dispersing the nanofillers into a polymeric matrix. The polymeric matrices mostly used in forming food packaging are synthetic nondegradable polymers (polyethylene, polypropylene, polyethylene terephthalate), degradable polymers (polyvinyl alcohol, poly(lactic acid), polyhydroxybutyrate), and biopolymers (polysaccharides, proteins) ([Vasile, 2018](#)). Biopolymer-based coating presents some critical issues related to water resistance and permeability. These issues can be addressed by incorporating reinforcing compounds, such as nanofillers, to create bio-nanocomposites ([De Azeredo, 2009](#)).

A well-dispersed packaging material with desirable properties can be formed by the selection of compatible film constituents (biopolymer and nanofiller) and by applying an appropriate manufacturing method. The selection of a film fabrication method for the effective dispersion of nanomaterials into the matrix polymer is still a significant barrier to the industrial upscaling of nanocomposite packing materials. [Table 2.2](#) summarizes some recent research studies and the techniques used for the preparation of nano-based food packaging films. Solvent casting or solution mixing is a popular technique for film forming. This method involves vigorously stirring the biopolymer in a solution, followed by nanoparticle ultrasonication in the polymer solution. The polymer nanoparticle solution is then cast into a mold and left for subsequent evaporation of the solvent. The solvents are effectively evaporated using microwaves, hot air ovens, or vacuum driers, and the produced film is easily peeled off the mold ([Suvarna et al., 2022](#)). This technique facilitates the homogeneous distribution of nanoparticles within the polymer while facilitating the formation of filler-rich layers ([Wang et al., 2020](#)). Since a volatile solvent is used for easy evaporation, sometimes this method might be toxic if organic solvents are used.

TABLE 2.2 Different Methods Used in Recent Studies for the Preparation Based Food Packaging [↗](#)

<i>NANOMATERIAL</i>	<i>POLYMER</i>	<i>METHOD FOR PREPARATION OF NANO-BASED PACKAGING</i>	<i>PROPERTIES OF NANO-BASED PACKAGING</i>	<i>REF</i>
Cellulose nanoparticles	Polylactic acid	Solution casting	Improved oxygen and water vapor permeability, higher UV protection, Decrease in transparency	I
Magnesium oxide nanoparticles	Chitosan	Solvent casting method	Elastic modulus and tensile strength of nanocomposites improved by about 38% and 86%, respectively; improved moisture barrier properties and UV shielding	I
Magnesium oxide nanoparticles	Polylactic acid biopolymer	Solvent casting method	Transparent, oxygen barrier properties and tensile strength	S

<i>NANOMATERIAL</i>	<i>POLYMER</i>	<i>METHOD FOR PREPARATION OF NANO- BASED PACKAGING</i>	<i>PROPERTIES OF NANO- BASED PACKAGING</i>	<i>REF</i>
			enhanced by about 25% and 29%, respectively; water vapor barrier properties lowered by about 25%; antibacterial properties (about 46% of E. coli culture damaged after 12 h treatment)	
Mahua oil-based polyurethane and chitosan	Zinc oxide nanoparticles	Solvent casting method	Improved tensile strength and stiffness, enhanced antibacterial property, improved gas and water barrier characteristics, increased the shelf life of	J Re

<i>NANOMATERIAL</i>	<i>POLYMER</i>	<i>METHOD FOR PREPARATION OF NANO-BASED PACKAGING</i>	<i>PROPERTIES OF NANO-BASED PACKAGING</i>	<i>REF</i>
			carrots wrapped in the nanocomposite film for up to 9 days	
Nanoclay particles	Carboxymethyl cellulose/polyvinyl alcohol	Solvent casting evaporation method	Improved tensile strength (from 11.54 to 25.01MPa) and decreased water vapor permeability and oxygen permeability	[10]
ZnO nanoparticles	Chitosan-cellulose acetate phthalate films	Solvent casting method	Increased thermal stability and low surface wettability, 30–50% biodegradation of the nanocomposite films after 28 days	[11]
Silver nanoparticles	Polyvinyl chloride	Electrospinning	Chitosan-based composite	[12]

<i>NANOMATERIAL</i>	<i>POLYMER</i>	<i>METHOD FOR PREPARATION OF NANO- BASED PACKAGING</i>	<i>PROPERTIES OF NANO- BASED PACKAGING</i>	<i>RE</i>
synthesized via chitosan			nano-layers used for meat packing with enhanced antimicrobial properties due to the addition of silver nanoparticles	
Bentonite nanoparticles	Polylactic acid	Melt processing	Improved barrier properties against water vapor transportation and higher elongation ability without forming tear	Ol et
Copper oxide nanoparticles	Chitosan and polyvinylpyrrolidone	Casting method	The addition of the nanoparticles decreased the crystallinity and swelling capacity of the	Al :

<i>NANOMATERIAL</i>	<i>POLYMER</i>	<i>METHOD FOR PREPARATION OF NANO- BASED PACKAGING</i>	<i>PROPERTIES OF NANO- BASED PACKAGING</i>	<i>RI</i>
			nanocomposite system	

The extrusion or melt processing method involves compounding nanofillers and polymers using an extruder, either a single or twin screw. This technique blends the constituents in a molten state, utilizing shear and elongational stresses within the mixer to break up filler agglomerates and evenly disperse them throughout the polymer matrix ([Vasile, 2018](#)). The extrusion method is generally performed in three steps: first, feeding, then kneading, and, lastly, heating toward the exit of the machine. During the feeding stage, the constituents for film formation are added to the feeding zone along with compressed air. This process typically requires minimal water or solvents; thus, it is often referred to as a dry process. Plasticizers such as sorbitol or polyethylene glycol (PEG) are sometimes introduced to enhance the flexibility of the film. During the kneading stage, the temperature, strain, and density of film-forming mixture increase. The final heating stage applies thermal energy between 120 and 170°C, which is usually higher than the glass transition temperature ([Suhag et al., 2020](#)). This method is considered both economically and environmentally friendly due to its use of non-toxic solvents ([Dhar et al., 2014](#)). Further, electrospinning and electrospraying are generally used methods to form a non-woven web of micro- or nano-fibers. This technique involves using high electric potential to expel (electrospinning) or spray (electrospraying) polymer solutions at standard temperature and pressure conditions, forcing the flow of solution through a nozzle to form a jet stream. Electrospinning produces micro- and nanostructured fibers with various morphologies, while electrospraying generates particles ranging from nanometers to a few

micrometers ([Bavatharani et al., 2021](#)). Key factors to consider in this method include the electric potential, flow rate, properties of the solution (like surface tension, viscosity, and conductivity), the distance separating the collector and nozzle, and surrounding chamber conditions (such as air velocity, humidity, temperature) ([Orsuwan & Sothornvit, 2018](#)).

2.5 ACTIVE AND INTELLIGENT PACKAGING USING NANOTECHNOLOGY

2.5.1 Active Packaging

Active packaging is intended to engage with food or the surrounding environment in a controlled manner to prolong shelf life, enhance safety, and maintain the quality of food products ([Roopa et al., 2023](#)). Nanotechnology is essential for facilitating these functionalities, primarily through the incorporation of nanomaterials that can absorb or release substances based on the requirements of the food product. Some key areas where nanotechnology is used in active packaging are as follows:

2.5.1.1 Antimicrobial Packaging

A major application of nanotechnology in active packaging is the incorporation of antimicrobial nanoparticles, which help inhibit the growth of harmful bacteria, fungi, and other microorganisms that can lead to food spoilage or contamination ([Kraśniewska et al., 2020](#)). Various nanomaterials, such as silver, titanium dioxide, zinc oxide, and copper oxide nanoparticles, have been recognized for their antimicrobial properties. These nanomaterials prevent the growth of bacteria, molds, and yeasts on food surfaces, thereby minimizing spoilage and prolonging shelf life. For instance, silver nanoparticles incorporated into polymer films can inhibit the growth of *E. coli* and *Listeria* in packaged foods such as meat,

dairy products, and ready-to-eat meals ([Chawla et al., 2021](#)). ZnO-NPs are effective against a broad spectrum of bacteria, including *Salmonella* and *Staphylococcus aureus*. In addition, they possess UV-blocking properties, which help protect food from photodegradation ([Vieira et al., 2022](#)). CuO-NPs are capable of combating foodborne pathogens such as *Listeria monocytogenes*. These nanoparticles can be integrated directly into the packaging material or applied as a coating on the packaging surface ([Dash et al., 2022](#)). By actively preventing the growth of microorganisms, antimicrobial nanoparticles help prolong the shelf life of food, lower the risk of contamination, improve food safety, and decrease the likelihood of foodborne illnesses.

2.5.1.2 Oxygen Scavengers

Oxygen is a major factor that contributes to the degradation and spoilage of food products. Excess oxygen in packaging can encourage the growth of aerobic bacteria, mold, and yeast, and it can also lead to the oxidation of fats and oils, resulting in rancidity ([Dey & Neogi, 2019](#)). Nanotechnology offers solutions through the development of oxygen scavengers that remove or reduce the oxygen levels inside the package, slowing down oxidation processes that lead to food spoilage, and maintaining food freshness, flavor, and color for a longer period. Iron oxide nanoparticles (Fe_2O_3 -NPs) are commonly used as oxygen scavengers. When exposed to oxygen, these nanoparticles undergo oxidation, thereby removing oxygen from the environment. This can help maintain the freshness of oxygen-sensitive foods like snacks, baked goods, and dairy products ([Dubourg et al., 2024](#)). TiO_2 -NPs possess photocatalytic properties, allowing them to absorb and break down oxygen when subjected to UV light. This property is harnessed in packaging systems to actively reduce oxygen levels and prevent oxidation ([Ahmed & Hasan, 2023](#)).

2.5.1.3 Moisture Regulators

Moisture content is essential in determining the shelf life of food products. Excess moisture can promote the growth of bacteria and mold, whereas insufficient moisture can cause food to dry out and lose its texture. Nanotechnology enables the development of moisture-absorbing materials that can regulate the humidity levels inside packaging, ensuring optimal conditions for food preservation. Nanomaterials, such as silica gel nanoparticles (SiO_2 -NPs) and nanoclay, are used as moisture regulators in food packaging ([Choudhary et al., 2022](#)). Their high surface area allows them to absorb and retain moisture, preventing the growth of mold and maintaining the desired texture of the food. They optimize humidity levels to maintain food quality and texture.

2.5.1.4 Ethylene Scavengers

Ethylene is a natural plant hormone that speeds up the ripening of fruits and vegetables. In active packaging systems, nanomaterials are utilized to absorb ethylene gas, which slows down the ripening and senescence processes in fruits and vegetables, thereby prolonging their shelf life. Nanoclays are effective in absorbing ethylene gas, making them a valuable addition to packaging materials for fresh fruits and vegetables. By slowing down the ripening process, nanoclay composites help reduce food waste and maintain product quality during storage and transport ([Liu et al., 2020](#)).

2.5.2 Intelligent Packaging

Intelligent packaging goes beyond the traditional role of packaging by incorporating sensors, indicators, and communication systems that can monitor and report the condition of the food. Nanotechnology plays a pivotal role in the development of smart packaging by enabling the integration of nanosensors and nanodevices that can monitor variations in the food environment, including temperature, gas composition, humidity, and microbial activity ([Tavker & Sharma, 2022](#)). Intelligent packaging systems employ nanotechnology to assess the condition of packaged food

and relay information to both consumers and producers. The following are key applications of nanotechnology in intelligent packaging:

2.5.2.1 Nanosensors

Nanosensors are devices capable of detecting and responding to physical, chemical, or biological changes in the environment at the nanoscale level. In intelligent packaging, nanosensors are utilized to monitor food quality in real time, offering insights into spoilage, contamination, or alterations in freshness. Gas sensors can detect variations in gas composition within the package, including the levels of oxygen, carbon dioxide, and ethylene. For example, carbon nanotube-based gas sensors can be used to detect the release of gases that indicate spoilage, such as ammonia or sulfur compounds ([Banerjee & Tirrell, 2023](#)). These sensors can alert consumers or retailers when food is approaching its expiration date. Similarly, pH sensors can indicate spoilage or contamination when food products change their pH. Nanoscale pH sensors, made from materials like gold nanoparticles or carbon nanotubes, can be integrated into the packaging to detect pH changes and provide a visual or electronic signal when the food is no longer safe to consume ([Balbinot-Alfaro et al., 2019](#)).

2.5.2.2 Time-Temperature Indicators (TTIs)

Time-temperature indicators are intelligent packaging devices created to track the total exposure of food products to temperature over time. These indicators can provide valuable information about the storage conditions and the freshness of perishable items. Nanotechnology facilitates the creation of highly sensitive and accurate TTIs. For example, TTIs based on gold nanoparticles can be designed to change color in response to temperature variations, serving as a visual indicator of whether the food has been subjected to unsafe temperature conditions ([Hu & Miao, 2022](#)). A color shift from red to blue may signify that the food has been stored above the recommended temperature, indicating possible spoilage. It ensures food safety and quality by providing a visual indicator of potential spoilage.

2.5.2.3 Freshness Indicators

Freshness indicators are intended to offer real-time insights into the quality and freshness of food products. They can detect the presence of gases related to spoilage or microbial activity, enabling consumers to make informed choices about the safety of the food. Nanocellulose, a renewable nanomaterial derived from plant fibers, is used to create freshness indicators that change color in response to the release of gases associated with food spoilage, such as ammonia or hydrogen sulfide ([Shao et al., 2021](#)). These indicators can be incorporated into packaging materials to offer a clear visual signal when the food is no longer fresh.

2.5.2.4 RFID Tags with Nanotechnology

Radio Frequency Identification (RFID) and Near Field Communication (NFC) technologies are being incorporated into intelligent packaging systems, allowing wireless communication between the packaging and external devices like smartphones or scanners ([El Matbouly et al., 2022](#)). These technologies can be enhanced with nanotechnology to create more efficient and cost-effective communication systems. Nanoscale RFID tags can be integrated into packaging materials to track and monitor the condition of food products throughout the supply chain. These tags can store information about the temperature, humidity, and freshness of the food, allowing retailers and consumers to access real-time data about the product's quality. Therefore, this technology aims to enhance traceability inventory management and reduce food fraud ([Figure 2.2](#)).

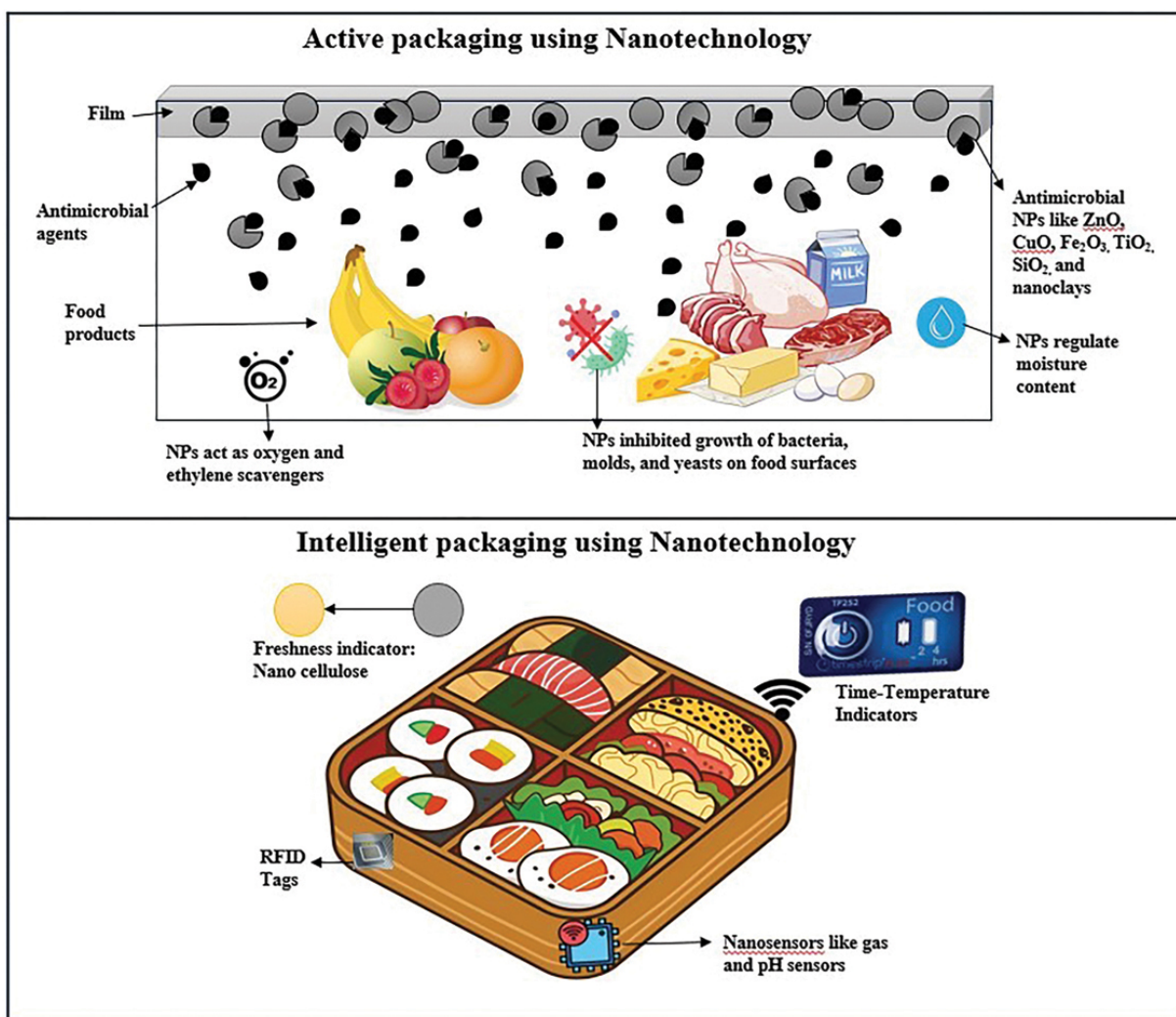


FIGURE 2.2 Development of nanotechnology-based active and intelligent food packaging. [↗](#)

2.6 APPLICATION OF NANOMATERIALS IN FOOD SYSTEMS

Nanotechnology has revolutionized food systems, particularly in packaging, processing, and food safety, by integrating nanomaterials that enhance performance and functionality. As discussed earlier, these materials, including metallic nanoparticles, nanoclays, and biodegradable nanocomposites, offer advanced solutions for reducing spoilage, extending

shelf life, and improving food quality and safety. The integration of nanotechnology into food systems has significantly advanced over the past two decades, particularly in food packaging, processing, and safety. Nanomaterials such as carbon nanotubes (CNTs), nanoclay, silicon dioxide (SiO_2), silver (Ag), titanium dioxide (TiO_2) and zinc oxide (ZnO) have been extensively researched for their ability to enhance the physicochemical properties of packaging materials, including improved strength, durability, flexibility, and barrier functions ([Chaudhary et al., 2020](#)). These enhancements not only maintain color, flavor, moisture content, and texture and enhance shelf life but also reduce microbial contamination through mechanisms such as cell membrane disruption and the Trojan horse effect ([Sharma et al., 2017](#); [Singh et al., 2017](#)).

In food packaging, nanomaterials are employed in various forms, such as nano-coatings and nanocomposites. For instance, AgNPs and ZnO are incorporated into packaging films to provide antimicrobial properties, effectively inhibiting the production of spoilage-causing bacteria that further extend the freshness of meat, dairy, and fresh produce ([Rossi et al., 2017](#); [Vilarinho et al., 2018a](#); [Nile et al., 2020](#)). ZnO nanoparticles, generally, are favored for their lower toxicity and cost-effectiveness compared to AgNPs, while they also offer UV protection to prevent oxidative spoilage. Nanoclays, such as montmorillonite, reduce moisture and oxygen permeability and further improve the barrier properties of packaging films, which is crucial for preserving the crispness and freshness of snacks and processed foods ([Shankar et al., 2024](#)). In food processing, nanoencapsulation techniques have advanced the delivery of bioactive compounds, flavors, and nutrients. Lipid-based and polymeric nanocarriers facilitate the controlled release and targeted delivery of antioxidants, vitamins, and other functional compounds. This technology enhances the stability and bioavailability of these ingredients in food products ([Bahrami et al., 2020b](#); [Nile et al., 2020](#)). This technology ensures prolonged flavor release in beverages and other consumables, thereby improving overall product quality. Furthermore, nanomaterials like titanium nitride (TiN) nanoparticles, approved by the European Food Safety Authority (EFSA),

are utilized in polyethylene terephthalate (PET) bottles to prevent CO₂ leakage in carbonated beverages, enhancing product stability ([Zhang et al., 2017](#)). SiO₂ nanoparticles are employed to create lightweight, heat-resistant packaging materials such as Durethan, which offer superior barrier properties that minimize the need for multi-layer packaging ([Tang et al., 2019](#); [Pandey et al., 2020](#)). Photocatalytic nanomaterials, including TiO₂ and ZnO, are incorporated into the packaging to degrade organic contaminants and eliminate microbes through ROS generation, providing an additional layer of food safety ([Kuswandi & Moradi, 2019](#)).

2.6.1 Nanomaterials in Food Packaging: Organic, Inorganic, and Hybrid Approaches

Various organic, inorganic, and hybrid nanomaterials ([Table 2.3](#)) are incorporated into the design of advanced food packaging systems. These materials are crucial in mitigating both quantitative and qualitative food losses by enhancing the mechanical properties and barrier efficiency of the packaging.

2.6.1.1 Organic Nanomaterial

Starch, a polysaccharide made of amylose and amylopectin, is gaining popularity in food packaging (bio-based) due to its environmental compatibility, low cost, tastelessness, and transparency. Thermoplastic starch films demonstrate enhanced mechanical properties in comparison to films made from other polysaccharides and proteins; however, their hydrophilic nature results in high water vapor permeability and diminished strength. For example, thermoplastic cornstarch films combined with chitosan oligomers have demonstrated notable antimicrobial properties, making them particularly suitable for packaging perishable goods, including meats and ready-to-eat meals. These films represent a sustainable option for extending the freshness of packaged products while maintaining their safety and integrity ([Silva et al., 2018](#)). Blending starch with nanoclays, particularly organically modified montmorillonite (OMMT), can enhance

properties, though OMMT tends to agglomerate, leading to poor performance ([Biduski et al., 2017](#)). Unmodified hydrophilic nanoclay has shown significant improvements in mechanical and barrier properties, as shown by baby spinach leaves, by improving mechanical strength and reducing water vapor transmission ([Resano-Goizueta et al., 2018](#)). Effective dispersion of clay platelets in starch can be achieved by hydrogen bonding interactions with sodium cations in MMT – Na⁺ ([Chaudhary et al., 2020](#)), although challenges remain. [Kim and Song_\(2018\)](#) found that surface modification with polydopamine of MMT-Na⁺ improves interactions with starch, enhancing tensile strength, and is used for packing fresh produce and dairy products during handling in the supply chain.

TABLE 2.3 Application of Different Nanomaterial-Reinforced Polymer M
Food Industry [!\[\]\(ad01d781d906bb000cbb7bfc2c580c38_img.jpg\)](#)

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>API I</i>
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<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
Nanocellulose	Chitosan or PVA	Improved antifungal and antibacterial properties Enhanced tensile strength and thermal stability	Food packaging, wound dressings
	Starch-PVA film	Solubility, WVP, and water absorption decreased	Vegetable packaging, pharmaceuticals
	Poly(3-hydroxybutyrate)	Blend with 3% CNCs showed optimal optical, thermal, and mechanical properties	Packaging for food, pharmaceuticals
	Chitosan, Starch-PVA	Biocompatible with high water uptake; used in food packaging.	Balloon catheters, wound dressings

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATION</i>
Nano starch	Chitosan film	Reduced swelling index, moisture content, and solubility, radical scavenging activity of 91.5%	Food packaging applications
	Cornstarch or mango kernel	Enhanced opacity, modulus, and tensile strength; reduced WVP by ~15%	Food packaging

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
Protein Nanoparticles	Zein nanoparticles in whey protein isolates	Improved moisture barrier and enhanced mechanical properties; decreased fractional free volume and hydrophobicity	Wrapping
	HPMC films and chitosan nanoparticles	Increased storability	Food packaging
	chitosan/tripolyphosphate nanoparticles mixed in HPMC films	Enhanced mechanical properties; improved thermal stability, barrier properties, and WVP	Meat packaging

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATION</i>
Chitosan	HPMC	Coating agent for mandarin, strawberries, and fresh fruits; acts as an anti-fungicide	Food packaging
	Tripolyphosphate	Enhanced mechanical properties; improved thermal stability, barrier properties, and WVP	Meat packaging
Carbon Nanotubes (CNTs)	ZnO-modified PVA film	Enhanced tensile strength by 116%; improved barrier properties, antibacterial properties, and increased thermal stability	Medical packaging
	Cinnamaldehyde film and polylactic acid	Enhanced resistance against UV, glass transition temperature reduced	Packaging of sensitive food

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
	Biopolymer, PVC	Improved electrical, optical, thermal, and mechanical properties	Food packaging
	Biopolymers	Increased mechanical and thermal properties	Staple packaging
	EVOH	Enhanced gas barrier properties and thermal stability	Food packaging
	PVC	Increased thermal stability and antimicrobial properties	Food containers
	Starch-based Polymers	Enhanced biodegradability and mechanical properties	Eco-friendly packaging
	PET	Enhanced UV resistance and barrier properties	Packaging for sensitive products
	CuO	Increased thermal stability	Food packaging

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
		and antimicrobial properties	
Graphene	PE	Improved gas barrier properties and thermal stability	packaging for food
	PET	Improved oxygen barrier and UV resistance	Packaging for sensitive electronics

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
Nanoclay/Montmorillonite		Reduced	Permeability
	Polylactic acid	migration and WVP, enhanced biodegradation	nanocomposites

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATION</i>
	Surface-modified polylactic acid	Improved tensile strength, altered degradation starting temperature	Prolonged shelf life
	Fish protein	Improved barrier properties, solubility, WVP, solubility, and tensile strength	Freshness, food safety
	Rice flour/gelatin/catechin-lysozyme	Reduction in microbial growth and lipid oxidation, enhanced film solubility, and mechanical properties	Food safety
	Citric acid/whey protein, starch	Improved thermal, structural, mechanical, and morphological properties	Protein preservation
Zein nanoparticles	Whey Protein	Improved mechanical properties,	Wrapping, preservation, meat

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>API II</i>
		decreased hydrophobicity	

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATION</i>
AgNP	Starch-PVA film containing AgNPs	Enhanced antimicrobial activity of fat-rich food products.	Packaging

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
	AgNPs entrapped with polyacrylic acid in chitosan/cellulose films	Improved degradation and antimicrobial activity	Food packaging
	Polypropylene film	Improved thermal degradation and crystallization, enhanced antibacterial activity	Medical packaging
	Polysaccharide-based Films	Enhanced antibacterial activity, improved absorption, and decomposition of ethylene in fruits and vegetables	Food packaging
	PVA-starch	Improved antimicrobial, mechanical, and barrier properties	Food packaging
	Potato starch films	Reduced WVP and solubility, improved barrier properties,	Balancing

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLICATIONS</i>
		increased tensile strength, and antimicrobial activity	
	Cellulose acetate	Reduces oxygen flow inside packed containers	vegetables

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLI- CATIONS</i>
TiO₂	Xylan/PVA	Improved barrier properties and mechanical properties	D

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLIED</i>
	Poly(lactic acid)	Reduction in WVP, increased elongation, and opacity	Packaging
	TiO ₂	Modified light transmission characteristics, increased film flexibility, and observed new crystalline phases	Vegetable packaging
	Starch/cinnamom oil, soluble soybean polysaccharide, wheat gluten	Improved barrier and mechanical properties, enhanced antimicrobial properties	Packaging
	Citric acid/whey protein	Improved thermal, structural, morphological, and mechanical properties	Packaging
	Poly(3-hydroxybutyrate)	3% CNCs showed optimal optical, thermal, and mechanical properties	Packaging for vegetables

<i>NANOMATERIAL</i>	<i>FILM MATRIX</i>	<i>ALTERED PROPERTIES</i>	<i>APPLIED</i>
CuO	PVC	Increased thermal stability and antimicrobial properties	Food packaging
MgO	Cellulose Acetate	Enhanced antibacterial activity and UV-blocking	Starch packaging

AgNP = Silver nanoparticle, *CNC* = Cellulose nanocrystals, *CNT* = Carbon nanotube, *CuO* = Copper oxide, *EVOH* = Ethylene-vinyl alcohol copolymer, *HPMC* = Hydroxypropyl methyl cellulose, *MgO* = Magnesium oxide, *NC* = Nanocrystals, *PE* = Polyethylene, *PET* = Polyethylene terephthalate, *PVA* = Polyvinyl alcohol, *PVC* = Polyvinyl chloride, *TiO₂* = Titanium-di-oxide, *WVP* = Water vapor permeability, *ZnO* = Zinc oxide

Nanostarch, produced through physical and chemical treatments, includes nanoparticles known as starch nanocrystals with dimensions below 300 nm ([Morán et al., 2021](#); [Yu et al., 2021](#)). These nanocrystals serve as fillers to improve the barrier, biodegradable, and mechanical properties of composites ([Dularia et al., 2019](#); [Campelo et al., 2020](#)). Methods like enzyme and acid hydrolysis are employed for nano starch production ([Silva et al., 2018](#)). Starch nanocrystals can enhance the flexible food packaging of fresh produce while reducing hydration issues. The integration of nanostarch has been shown to decrease permeability, which is crucial for enhancing the shelf life of moisture-sensitive products, that is, dairy items and fresh produce. Incorporating nanoparticles like *TiO₂*, *ZnO*, and graphene significantly boosts the performance of native starch, which has inherent weaknesses ([Sadeghizadeh-Yazdi et al., 2019](#)). For instance, adding graphene oxide to starch/PVA composites improves water vapor

permeability and mechanical properties applied to liquid and moist foods ([Wu et al., 2019](#)). Pea starch nanocrystals blended with PVA are used in dairy and liquid foods to enhance physical properties. Moreover, biodegradable films developed from cassava starch and reinforced with rosemary nanoparticles have shown promising results in packaging applications, offering both antimicrobial efficacy and preservation of food quality. Despite its benefits, native starch is susceptible to UV and moisture, with nanoparticles helping to mitigate these issues ([Li et al., 2020](#); [Rajak et al., 2019](#)). Chemical modifications like acetylation further enhance its properties ([Wang et al., 2019](#)). Acid-hydrolyzed starch nanocrystals improve the strength and barrier performance of thermoplastic films, making them suitable for fruit and vegetable wrapping applications. [Muthulakshmi et al. \(2021\)](#) demonstrated that combining chitosan with other natural polymers and fillers enhances its physicochemical properties, making it suitable for perishable food packaging applications. These composite films offer effective barriers against moisture and gases while providing antimicrobial properties that extend the shelf life of fruits, vegetables, and meat products ([Wang et al., 2018](#); [Tian & Liu, 2020](#)). Adding natural additives like carotenoids further improves the antioxidant and antimicrobial functions of chitosan films, enhancing their preservation capabilities and making them suitable for active packaging ([de Souza Mesquita et al., 2020](#)). These films are particularly useful for wrapping fresh produce and meat, where their antimicrobial properties help inhibit bacterial growth and spoilage ([Wang et al., 2018](#); [Tian & Liu, 2020](#)). [Vilela et al. \(2019\)](#) explored the use of nanocellulose-based films in active and intelligent packaging systems, highlighting their potential to incorporate sensors for monitoring food quality, such as humidity levels. For instance, chitosan films infused with oregano essential oil have been developed to protect tomatoes from spoilage while maintaining their quality ([Chen et al., 2021](#)). [Silva et al. \(2020\)](#) also emphasized that nanocellulose composites improve the barrier properties and tensile strength of packaging materials, making them highly suitable for maintaining food quality during transportation and storage. Nanocellulose has been applied as a coat on

kraft paper, significantly enhancing its resistance to moisture and oxygen, which is critical for maintaining the food quality of fresh produce during storage ([Fotie et al., 2020](#); [Lengowski et al., 2023](#)).

Protein-based films have been combined with other biopolymers to enhance their barrier and mechanical properties. The incorporation of nanomaterials further improves their functionality, especially for active packaging of fresh produce, that is, fruits and vegetables that require water vapor control and antimicrobial activity ([Shanmugam et al., 2022](#); [Tian & Liu, 2020](#); [Shanmugam, 2024](#)). Similarly, the inclusion of montmorillonite (MMT) in soy protein films, along with clove essential oil, has proven effective in preserving refrigerated bluefin tuna fillets, highlighting the adaptability of MMT across diverse food preservation applications. These films, commonly used for packaging snacks and bakery products, provide a biodegradable alternative to conventional plastic packaging while ensuring the quality of the food ([Shanmugam et al., 2022](#)).

2.6.1.2 Inorganic Nanomaterial

The incorporation of inorganic nanoparticles into food packaging has emerged as a significant advancement, contributing to improved food safety and prolonged shelf life. Nanoparticles like Ag, ZnO, and TiO₂ are incorporated into packaging materials for their strong antimicrobial properties, which help prevent the production of spoilage-causing microorganisms ([Omerović et al., 2021](#); [Anvar et al., 2021](#); [Mulla et al., 2021](#)). Silver nanoparticles, in particular, are effective at minimizing bacterial contamination, helping to maintain the freshness of packaged foods ([Tavakoli et al., 2017](#); [Ahmad et al., 2021](#)). Additionally, their integration into biodegradable films improves mechanical strength and enhances gas and moisture barrier properties, which are critical for food preservation ([Dash et al., 2022](#); [Suvana et al., 2022](#)).

Combining inorganic nanoparticles with natural antioxidants, including plant-derived polyphenols and essential oils, further boosts the antimicrobial and antioxidant functions of packaging materials, thereby

enhancing the shelf life of meat and seafood while promoting environmentally sustainable solutions ([Minina & Sinelnikova, 2023](#)). These active packaging systems can be tailored to the specific preservation requirements of different food products, offering targeted protection against spoilage and contamination ([Omerović et al., 2021](#); [Dash et al., 2022](#)). Nanocomposites have also been shown to reduce the pasteurization temperatures required for certain foods, such as orange juice, allowing for better preservation of nutritional quality while ensuring food safety. Beyond antimicrobial functions, nanomaterials serve as oxygen scavengers and moisture regulators, essential for maintaining the quality of perishable goods ([Alsaqqa, 2020](#); [Tsagkaris et al., 2018](#)). Furthermore, nanoparticle-based smart packaging systems can monitor food freshness and signal spoilage, increasing consumer safety ([Sharma et al., 2017](#); [Tsagkaris et al., 2018](#)). ZnO nanoparticles not only offer antimicrobial benefits but also strengthen packaging materials and enhance their barrier properties. For instance, ZnO incorporated into chitosan-coated polyethylene films has been demonstrated to enhance the shelf life of okra by maintaining quality ([Al-Naamani et al., 2018](#)). Moreover, combining ZnO with natural antioxidants improved both the antioxidant and antimicrobial properties of packaging, further ensuring food quality and safety ([Dash et al., 2022](#); [Minina & Sinelnikova, 2023](#)). TiO₂ nanoparticles are particularly valued for their photocatalytic activity, which helps break down organic contaminants, thereby enhancing food safety ([Mulla et al., 2021](#)). The development of nanocomposite films that combine inorganic nanoparticles with biodegradable polymers, such as MMT clay with silver and cerium oxide nanoparticles in carrageenan-based films, offers a significant step forward. These films improve mechanical strength and provide antimicrobial protection while meeting the increased demand for bio-based food packaging solutions ([Genecya et al., 2023](#)).

2.6.1.3 Hybrid Nanomaterial

Nanohybrid-based bio-nanocomposite films, created by combining inorganic–inorganic, organic–organic, and inorganic-organic nanohybrids with biopolymers, present an innovative solution for food packaging. These hybrid materials also play a key role in the controlled release of bioactive compounds. Encapsulated essential oils or antioxidants within polymeric nanocomposites can gradually release these agents, preserving the food's flavor and nutritional content and providing antimicrobial effects ([Eleftheriadou et al., 2017](#)).

A key advantage of hybrid nanomaterials is their antimicrobial properties. For example, AgNPs integrated into biopolymers like chitosan or gelatin show strong antimicrobial activity against various foodborne pathogens, reducing spoilage and extending the shelf life of fresh produce and dairy products ([Kowsalya et al., 2021](#); [Suvarna et al., 2022](#)). AgNPs enhance the mechanical strength and flexibility of packaging materials and have been successfully incorporated into films for meat products, reducing spoilage and maintaining quality ([Basavegowda & Baek, 2021](#)). Nanoclays, another key additive, improve barrier properties by limiting moisture and gas transmission, thereby reducing food spoilage caused by oxygen and humidity ([Sadeghizadeh-Yazdi et al., 2019](#)). When combined with biopolymers, nanoclays contribute to the development of biodegradable packaging, aligning with sustainability goals ([Vilarinho et al., 2018a](#)). Polyamide films reinforced with nanoclays exhibit improved oxygen barrier properties, making them suitable for packaging oxygen-sensitive products such as meat and dairy. Additionally, nanoclay composites have been used in the packaging of carbonated beverages, where their rigidity and barrier properties help maintain carbonation levels ([Agriopoulou et al., 2020](#)). Chitosan-based nanoclay composites have also demonstrated significant antimicrobial activity against common foodborne pathogens, making them ideal for packaging perishable items like fruits and vegetables ([Suvarna et al., 2022](#)). Hybrid nanomaterials enable the controlled release of active compounds, such as antioxidants or preservatives, prolonging food quality and safety ([Giannakas et al., 2023](#)). For instance, carboxymethyl cellulose-based nanocomposites reinforced with montmorillonite can deliver

antimicrobial agents, making them suitable for packaging ready-to-eat meals, fresh produce, and dairy products ([Trache et al., 2020](#)). Additionally, zinc oxide (ZnO) nanoparticles incorporated into polymer matrices like polyvinyl alcohol (PVA) provide UV-blocking and antimicrobial properties, further enhancing their suitability for packaging fresh produce and dairy products ([Ma et al., 2024](#)).

Smart packaging systems, an emerging trend, utilize hybrid nanomaterials to monitor food quality in real time through sensors that detect environmental changes such as pH or temperature fluctuations ([Anvar et al., 2021](#)). This technology improves food safety and reduces waste by providing real-time indicators of the freshness of fruits and vegetables. Another example of hybrid nanomaterials in packaging is CMC-based nanocomposites with ϵ -poly-L-lysine and montmorillonite, which exhibit strong antimicrobial properties for meat packaging ([He et al., 2020](#)). Zinc oxide nanoparticles in CMC-gelatin films reduce oxygen permeability, which is crucial for maintaining fresh produce freshness ([Zafar et al., 2022](#)). Nanohybrid biocomposite films, formed by combining various nanohybrids with biopolymers, offer enhanced thermal, barrier, and mechanical properties, suitable for extending the shelf life of packed food. Biopolymer-based nanocomposites, such as those formed with chitosan or cellulose, offer dual benefits of antimicrobial activity and biodegradability, catering to the increasing demand for sustainable packaging solutions ([Basavegowda & Baek, 2021](#); [Vilarinho et al., 2018b](#)). Additionally, graphene oxide (GO), when combined with biopolymers, significantly improves the barrier properties of packaging films, making them ideal for moisture-sensitive food products ([Das et al., 2023](#)).

2.7 POTENTIAL RISKS OF USING NANOCOMPOSITES IN PACKAGING

The use of nanocomposites in food packaging holds promise for improving food safety, extending shelf life, and enhancing product quality. However, potential risks, particularly concerning human health and environmental impact, require careful evaluation. The primary concerns involve the movement of nanoparticles from packaging into food, their toxicological effects, and their environmental consequences. A key issue is the migration of nanoparticles into food products. Research indicates that the composition of the packaging and the properties of the food can influence the extent of this migration ([Huang et al., 2018](#); [Bumbudsanpharoke et al., 2015](#)). For example, while silver and zinc oxide nanoparticles incorporated into poly(lactic acid) (PLA) films exhibit antimicrobial properties, they also pose a risk of leaching into food, leading to unintended consumer exposure ([Chu et al., 2017](#)). This raises concerns about nanoparticle accumulation in human tissues, which may result in adverse effects, including inflammation and oxidative stress ([Piperigkou et al., 2016](#); [Wagner et al., 2017](#)).

◀ The incorporation of nanomaterials in food packaging raises significant concerns regarding human exposure and potential health risks. Key exposure pathways identified include inhalation, dermal contact, ingestion, and indirect environmental contamination ([Ahmed & Hasan, 2023](#); [Gupta et al., 2024](#)). Ingestion is a primary exposure route, as nanoparticles can migrate into food from packaging material, especially in prolonged storage, acidic conditions, and at high temperatures ([Itrat et al., 2025](#)). Research has demonstrated that nanoparticles such as Ag, TiO₂, and ZnO can migrate into food products, with Ag nanoparticles being particularly susceptible to detachment in high-moisture foods ([Eremeeva, 2024](#)). Mechanical degradation of packaging materials can also release nanomaterials (NMs), particularly in flexible films and coatings prone to wear and tear ([Wohlleben et al., 2024](#)). During the manufacturing, handling, and disposal of packaging, nanomaterials can become airborne, generating fine dust or aerosol particles. This occurrence poses an inhalation hazard for both workers and consumers, especially when packaging materials are cut or torn ([Dhall et al., 2024](#)). Dermal exposure is another potential pathway, as direct contact with packaging materials may allow NMs to penetrate the skin,

particularly in the case of wounds or prolonged exposure. Studies suggest that nanoparticles such as Ag and TiO₂ can permeate the outer skin layers, posing potential health risks ([Cirillo et al., 2024](#)). This risk is further heightened with products that remain in prolonged contact with the skin, such as cosmetics or pharmaceuticals, where NM absorption is more likely.

The leaching of metal-based nanoparticles, such as copper and silver, from food packaging into food products has emerged as a significant health concern. Research indicates that these nanoparticles are susceptible to leaching into food, with migration rates particularly heightened under acidic conditions ([Ahari & Lahijani, 2021](#); [Ahmad et al., 2021](#)). Generally, the European Food Safety Authority (EFSA) has established a migration limit for silver nanoparticles, capping their presence at 0.05 mg/kg in food ([Istiqola & Syafiuddin, 2020](#)). Studies on copper oxide nanoparticles incorporated into biopolymer matrices show migration rates ranging from 4.47 to 5.00 mg/dm² when exposed to 3% acetic acid, significantly surpassing migration in aqueous conditions ([Bumbudsanpharoke et al., 2024](#)). Similarly, zinc oxide nanoparticles exhibit varying migration levels, heavily influenced by the type of food simulant, underscoring the complex interaction between food composition and nanoparticle migration. Several factors impact the migration behavior of NPs from packaging materials, including temperature, food properties, and the chemical compatibility of the NPs with food components. Elevated temperatures generally accelerate diffusion, leading to increased NP migration into food ([Salehiyan & Ray, 2019](#); [Mileo et al., 2024](#)). Further, the hydrophilic or hydrophobic nature of nanomaterials plays a key role in their distribution: hydrophilic nanoparticles tend to remain in aqueous environments, while hydrophobic nanoparticles migrate more readily into lipid-rich foods. Desorption is another key mechanism facilitating NP migration, where nanoparticles initially adhered to the surface of packaging materials are released into food. This process can be exacerbated by mechanical stress, abrasion, or temperature fluctuations, all of which may compromise the structural integrity of packaging materials and promote nanoparticle release.

Therefore, ensuring the mechanical durability of packaging materials is essential to mitigate the migration of nanoparticles into food products.

Inhalation of nanomaterials can negatively impact lung health, potentially causing asthma, bronchitis, emphysema, and even cancer while also posing risks for Alzheimer's and Parkinson's disease and other neurological disorders. Dermal exposure to these materials may lead to autoimmune conditions and dermatitis, indicating skin-related health concerns. Additionally, the ingestion of nanoparticles can adversely affect the gastrointestinal tract, resulting in serious conditions like colon cancer and Crohn's disease. Nanomaterials may also disrupt the lymphatic system, contributing to podoconiosis and Kaposi's sarcoma ([Chadha et al., 2022](#)). Nanomaterials in food packaging present environmental risks through improper disposal. When discarded in landfills, nanoparticles can leach into the soil and groundwater, accumulating and potentially harming soil microorganisms, plants, and aquatic ecosystems ([Zheng et al., 2022](#); [Mishra & Sundaram, 2023](#)). Silver nanoparticles, for instance, may disrupt microbial communities critical for nitrogen cycling ([Sarkar, 2022](#)). Additionally, the incineration of NM-containing packaging can release nanoparticles into the atmosphere, posing inhalation risks and contaminating soil and water ([Thakur & Kumar, 2023](#)). The persistence of nanoparticles like TiO_2 and ZnO raises concerns about bioaccumulation and long-term ecological effects ([El-Kalliny et al., 2023](#)). Moreover, nanoparticles entering aquatic systems through landfill leachate can harm marine life and complicate water purification processes ([Kahlon et al., 2018](#); [Sibiya et al., 2022](#)). Additionally, the toxicological profiles of many nanocomposites are not well understood. Although certain nanomaterials exhibit beneficial properties, their long-term health effects remain unclear ([Adeyeye, 2019](#)). The lack of comprehensive risk assessments complicates the regulatory landscape, as many nanocomposite materials are still in developmental stages, and their safety for food-contact applications has not been fully validated ([Huang et al., 2018](#)). While not all nanomaterials pose a risk, potential interactions with biological systems highlight the need for further investigation.

Environmental concerns related to food packaging materials must be studied properly. Over time, nanocomposites may degrade, releasing nanoparticles into the environment, potentially causing ecological harm ([Han et al., 2018](#)). The complete lifecycle of these materials, from production to disposal, must be evaluated to reduce their environmental impact, as nanoparticles released into ecosystems could disrupt biodiversity and ecological balance ([Han et al., 2018](#)). Additional research is necessary to fully understand the behavior of nanomaterials, particularly under conditions that may enhance their migration into food, such as acidic environments ([Chadha et al., 2022](#)). This migration raises concerns about systemic toxicity, as nanoparticles could accumulate in human tissues and cause health issues such as inflammatory responses, oxidative stress, and disruptions in cellular function ([Bajpai et al., 2018](#)). Despite extensive research efforts, the long-term consequences of human exposure to nanomaterials are still not well characterized.



2.8 FUTURE DIRECTIONS AND CONCLUSION

While nanotechnology offers the potential for creating more sustainable packaging solutions by reducing material usage and improving recyclability ([Saikanth et al., 2023](#)), the risk of environmental contamination through the release of nanoparticles into ecosystems remains a significant concern ([Harun-Ur-Rashid et al., 2023](#); [Jafarzadeh et al., 2024](#)). Comprehensive environmental risk assessments and the establishment of regulatory frameworks are necessary to manage the use of nanomaterials in food packaging ([Piperigkou et al., 2016](#); [Onyeaka et al., 2022](#)). The current regulatory framework for nanomaterials is inadequate, lacking universally accepted standards on a global level. In the European Union, the use of nanoparticles in food contact materials is regulated by the European Commission, which mandates that each nanoparticle undergo individual

safety assessments before market approval (EC 1935/2004; EC 10/2011). Despite these regulations, there is a critical need for a more comprehensive regulatory structure that specifically addresses the unique risks posed by nanotechnology in food applications ([Bajpai et al., 2018](#); [Onyeaka et al., 2022](#)). The growth of nanocomposite materials in the food industry is substantial; however, the number of legally authorized nanomaterials recommended for regular usage in functional consumables is rather small. The insufficiency of toxicological data highlighting the safety assessments and potential health risks of incorporating engineered nanoparticles in food packaging needs to be updated and released in the public domain in a timely manner. Further, more emphasis should be placed on the development of methodologies to detect and monitor the release and migration of NMs from the prepared products. The selectivity, sensitivity, and accuracy of these detection methods would enable the researchers to comprehensively study the risks and benefits of NMs incorporated in food and beverage packaging. Understanding the fate of these nanocomposites in the human or animal body is a complicated task that cannot be mimicked in simple cell cultures. The indulgence of variable food matrices, their interaction with the well-defined packaging materials, and the resultant behavior of this complex in the gastrointestinal tracts of different organisms need to be extensively explored. With the advent of newer cutting-edge technologies and a plethora of nanotechnological revelations, it is important to acknowledge that there is a great deal of unknown facts that can pose threats to food security and sustainability. Nanofabricated materials, while paving the way forward due to their improved physical, mechanical, and functional properties, need to be thoroughly inspected before letting them overpower the front line and dominate the field of food packaging ([Figure 2.3](#)).

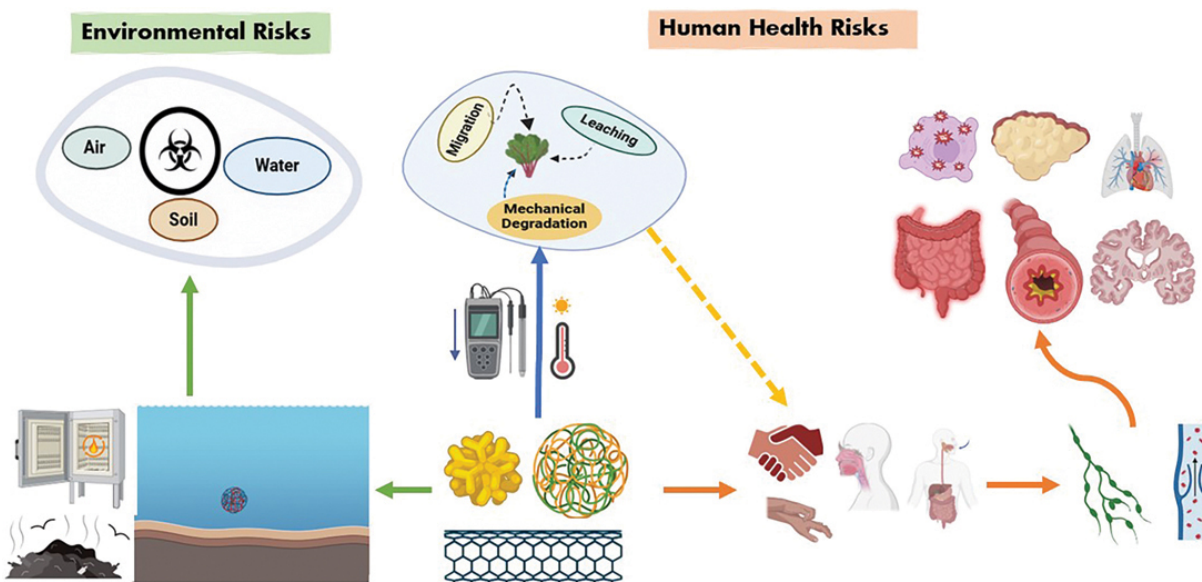


FIGURE 2.3 Potential environmental and human health risks of using nanocomposites in food packaging. [↗](#)

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3.1 INTRODUCTION TO ALIPHATIC POLYESTERS

Aliphatic polyesters have emerged as a significant class of biodegradable and biocompatible polymers, garnering substantial attention in the field of sustainable biomaterials. These polymers, characterized by their hydrolyzable ester bonds and relatively short aliphatic chains, offer a promising alternative to conventional petroleum-based plastics. The growing interest in aliphatic polyesters stems from their unique properties and potential to address environmental concerns associated with non-degradable polymers ([Asri et al., 2024](#)).

3.1.1 Overview of Aliphatic Polyesters

Aliphatic polyesters encompass a diverse range of polymers, including polylactide (PLA), polyhydroxyalkanoates (PHAs), poly(ϵ -caprolactone) (PCL), and polybutylene succinate (PBS) ([Nath et al., 2025](#)). The backbone of polymer molecules consists of carbon atoms, with each carbon atom capable of forming up to four covalent bonds. This allows for the creation of long chains, branched structures, or cross-linked networks, depending on the specific polymer type and synthesis method. The arrangement of these carbon atoms and the presence of other elements, such as hydrogen, nitrogen, oxygen, or halogens, contribute to the overall properties of the polymer ([Buensoz et al., 2024](#)). The molecular weight distribution of the polymer also plays a role in determining its properties. A narrow molecular weight distribution often results in more consistent and predictable material behavior, which is desirable for many applications ([Whitfield et al., 2019](#)).

Therefore, the molecular structure of aliphatic polyesters confers them with several advantageous properties, such as biocompatibility, biodegradability, thermoplasticity, low flammability, and dyeability. These characteristics make aliphatic polyesters suitable for a wide range of applications, from biomedical devices to packaging materials ([Stepanova & Korzhikova-Vlakh, 2022](#)).

3.1.2 Importance in Sustainable Biomaterials

As the demand for plastic products continues to rise globally, the development of biodegradable and non-toxic alternatives has become a pivotal area of research. Aliphatic polyesters, with their hydrolyzable ester bonds and derivation from renewable resources, offer a viable solution to these challenges ([Asri et al., 2024](#)). Their biodegradability plays a significant role in mitigating plastic waste accumulation in ecosystems, as the ester bonds in their structure enable them to break down under environmental conditions. This property is particularly advantageous in reducing the long-term environmental impact of plastic waste ([Bu et al., 2019](#)).

Another advantage of aliphatic polyesters is their derivation from renewable feedstocks, which reduces reliance on fossil fuels. Recent advancements have demonstrated the synthesis of these polymers from sustainable resources such as biomass-derived monomers, including lactones and dicarboxylic acids. For instance, ring-opening polymerization of bioderived lactones has been shown to yield aliphatic polyesters with controlled properties and high stereochemical retention ([Cairns et al., 2017](#)). The versatility of these polymers further enhances their appeal. They can be processed using a wide range of techniques, including electrospinning, film casting, and 3D printing, enabling their application across diverse industries, such as biomedical engineering and packaging ([Stepanova & Korzhikova-Vlakh, 2022](#)).

In addition to their environmental benefits, aliphatic polyesters exhibit tailorable properties that make them suitable for specific applications. Their mechanical strength, thermal stability, and degradation rates can be fine-tuned through monomer selection, polymer composition, and molecular weight control. For example, copolymerization with other monomers such as ϵ -caprolactone, succinic acid, 1,4-butanediol, glycolic acid, or trimethylene carbonate can enhance flexibility or accelerate degradation rates depending on the intended use ([Hillmyer & Tolman, 2014](#)). These properties are particularly valuable in biomedical applications such as drug delivery systems, suture threads, and scaffolds for tissue engineering. The biocompatibility of aliphatic polyesters ensures minimal adverse reactions when used in medical devices or implants. Furthermore, their controlled degradation profiles

allow for predictable breakdown within the body, making them ideal candidates for temporary biomedical applications ([Bu et al., 2019](#)).

Despite these advantages, certain challenges exist. For instance, the hydrophobic nature of many aliphatic polyesters can limit cell adhesion and biocompatibility in specific biomedical applications. To address this issue, surface modification techniques such as plasma treatment or chemical functionalization have been employed to improve cell affinity and overall material performance ([Bu et al., 2019](#)). In packaging applications, poor moisture resistance can restrict their use in high-humidity environments. Ongoing research focuses on developing composite materials or blends that retain the biodegradability of aliphatic polyesters while enhancing their barrier properties ([Marasinghe et al., 2024](#)).

3.1.3 Scope and Applications in Food Packaging

The food packaging industry has increasingly turned to aliphatic polyesters, such as polylactic acid (PLA) and polyhydroxybutyrate (PHB), as sustainable alternatives to conventional non-biodegradable plastics. These polymers exhibit several advantageous properties that make them suitable for food packaging applications. One of the most critical attributes is their barrier performance against oxygen (O₂), carbon dioxide (CO₂), and aromas, which are essential for maintaining food quality and extending shelf life. For instance, PLA and PHB have demonstrated good gas barrier properties comparable to polyethylene terephthalate (PET) and polypropylene (PP) when blended with other biopolymers or nanocomposites ([de Sousa Junior et al., 2022](#)).

The mechanical strength of aliphatic polyesters further supports their application in food packaging. PLA and PHB possess tensile properties, elongation at break, and elastic modulus values comparable to traditional plastics. For example, blending PLA with PHB or other biopolymers like polybutylene succinate (PBS) has been shown to enhance flexibility while maintaining strength, making these blends suitable for stretchable films used in packaging applications. Additionally, nanocomposites based on PLA-PHB blends exhibit superior impact resistance and elongation at break, addressing the mechanical demands of storage, handling, and transportation in the food industry ([De Luca et al., 2023](#)). For example, Luyao et al. tested the strength of a mixture of PLA and PHB using both slow and fast tests, and the result was that after mixing 20% of PHB with PLA, the polymer became three times more impact resistant, and the absorption was much better at 40% PHB ([Gao & Drozdov, 2024](#)). In another study, Jayven et al. created a PHB-based filler (5%) and mixed it with

PHA; the material became 15% stronger, and stretchability increased 57 times while being 38 times tougher. With 10% filler, strength is enhanced by 32%, and stretchability increased 128 times while being 84 times tougher ([Yeo et al., 2018](#)).

Biodegradability is another key advantage of aliphatic polyesters in food packaging. These polymers degrade under specific environmental conditions, reducing the accumulation of plastic waste in ecosystems. The ester bonds in their molecular structure are hydrolyzed over time, allowing microorganisms to metabolize the polymer fragments. This property aligns with global efforts to minimize the environmental footprint of packaging materials. However, the biodegradation rate can be influenced by factors such as polymer composition, crystallinity, and environmental conditions. Research has focused on optimizing these parameters to ensure effective degradation without compromising material performance during use ([J. Yang et al., 2024](#)).

Biocompatibility is an essential consideration for food safety in packaging applications. Aliphatic polyesters are inherently non-toxic and do not leach harmful substances into food products during storage. This quality ensures compliance with stringent regulatory standards for food contact materials. Furthermore, blending PLA or PHB with antimicrobial agents like ϵ -polylysine can enhance their ability to prevent microbial growth on packaged foods, thereby prolonging shelf life while maintaining safety standards ([J. Yang et al., 2024](#)). Despite these advantages, aliphatic polyesters face certain challenges in food packaging applications. Their poor moisture resistance can limit their use in high-humidity environments or for products requiring prolonged exposure to water vapor. To address this limitation, researchers have developed composite materials and blends incorporating hydrophobic additives or coatings that improve moisture barrier properties while retaining biodegradability. For instance, blending PLA with PBS or incorporating cellulose nanocrystals has been shown to reduce water vapor permeability significantly while maintaining mechanical strength and gas barrier performance ([De Luca et al., 2023](#)).

There are challenges related to moisture resistance and cost-effectiveness while exploring innovative formulations like nanocomposites and active packaging systems. As advancements in this field progress, aliphatic polyesters are expected to play an increasingly vital role in reducing the environmental impact of the food packaging industry ([Perera et al., 2020](#)).

3.2 CHEMICAL STRUCTURE AND PROPERTIES OF ALIPHATIC POLYESTERS

3.2.1 Basic Chemistry and Structure

Aliphatic polyesters represent a critical class of biodegradable polymers characterized by linear or branched chains containing ester functional groups (--COO--) within their backbone ([Wierckx et al., 2019](#)), as shown in [Figure 3.1](#). These polymers, including polylactide (PLA), polyglycolide (PGA), polycaprolactone (PCL), poly(lactide-co-glycolide) (PLGA), polybutylene succinate (PBS), and poly(butylene adipate-co-terephthalate) (PBAT), exhibit diverse structural configurations that directly influence their physicochemical and mechanical properties ([Stepanova & Korzhikova-Vlakh, 2022](#)). The ester linkages in their backbone confer hydrolytic degradability, while the aliphatic hydrocarbon segments between ester groups determine flexibility, crystallinity, and thermal stability. The ester linkages provide sites for hydrolytic degradation, contributing to the biodegradability of these polymers. The aliphatic nature of the carbon chains between ester groups influences properties such as flexibility and crystallinity. The molecular structure of polymers can be further categorized into amorphous and crystalline regions ([Qu et al., 2023](#)). Amorphous regions consist of randomly oriented polymer chains, while crystalline regions exhibit a more ordered arrangement. The degree of crystallinity significantly impacts the polymer's mechanical and thermal properties. For instance, higher crystallinity often leads to increased strength and stiffness but may reduce flexibility. The length of polymer chains, known as the degree of polymerization, is another critical structural feature ([Karpova et al., 2023](#)). Longer chains generally result in stronger intermolecular forces and increased crystallinity, which can enhance mechanical properties such as tensile strength and impact resistance. However, excessively long chains may also lead to processing difficulties due to high melt viscosity. Side chains or pendant groups attached to the main polymer backbone can significantly influence properties such as solubility, glass transition temperature, and reactivity ([Shukla et al., 2024](#)). In aliphatic polyesters, the presence of functional groups like carboxyl or amino groups can enhance hydrophilicity and provide sites for further chemical modifications or bioactive agent immobilization ([Bu et al., 2019](#)). For instance, PLA possesses a chiral carbon in its repeating unit ($\text{--O--CH(CH}_3\text{)--CO--}$), leading to stereoregular configurations (e.g., PLLA and PDLA) that enhance crystallinity and mechanical strength compared to amorphous PDLLA.

([Rasal et al., 2010](#)). In contrast, PCL contains a six-carbon repeating unit ($-(\text{CH}_2)_5-\text{COO}-$), with a long methylene sequence that increases chain flexibility and lowers its glass transition temperature ($T_g \approx -60^\circ\text{C}$), making it suitable for elastomeric applications ([Zaroog et al., 2019](#)).

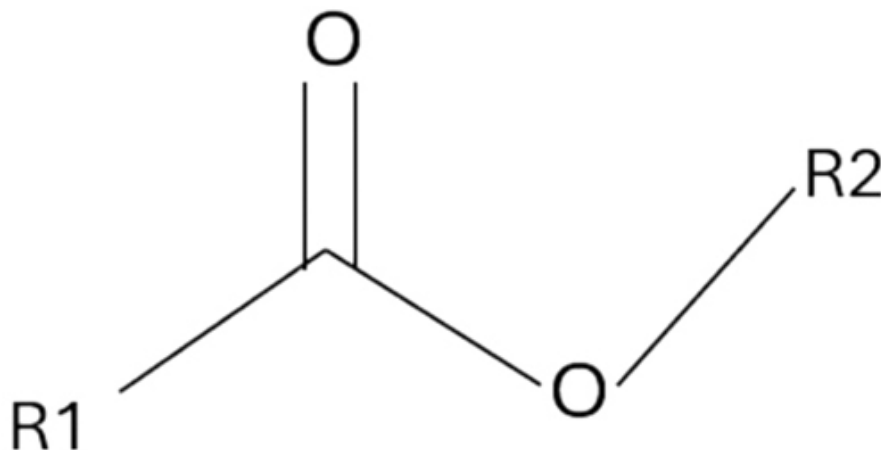


FIGURE 3.1 Chemical structure of aliphatic polyesters. [📄](#)

PGA, composed of glycolic acid units ($-\text{O}-\text{CH}_2-\text{CO}-$), exhibits high crystallinity (45–55%) and tensile strength due to its compact molecular packing, but its rapid degradation limits standalone use ([Rasal et al., 2010](#)). Blending or copolymerizing PGA with lactide (as in PLGA) modulates degradation rates by altering the lactide-to-glycolide ratio, which disrupts crystallinity and enhances hydrophilicity ([Marasinghe et al., 2024](#)). PBS, synthesized from succinic acid and 1,4-butanediol ($-\text{O}-(\text{CH}_2)_4-\text{O}-\text{CO}-(\text{CH}_2)_2-\text{CO}-$), combines moderate mechanical strength (tensile strength $\approx 30\text{--}40\text{ MPa}$) with biodegradability, making it suitable for packaging and agricultural films ([Rydz et al., 2014](#)). PBAT, a copolymer of adipic acid, terephthalic acid, and 1,4-butanediol ($-\text{O}-(\text{CH}_2)_4-\text{O}-\text{CO}-(\text{CH}_2)_4-\text{CO}-$ and aromatic terephthalate units), bridges the gap between aliphatic and aromatic polyesters, offering enhanced flexibility and processability while retaining biodegradability ([Stepanova & Korzhikova-Vlakh, 2022](#)).

Environmental factors such as microbial activity, pH, and humidity significantly influence the degradation of aliphatic polyesters. Hydrolysis of ester bonds proceeds faster in amorphous regions, leading to bulk erosion, while crystalline domains resist degradation, resulting in surface erosion ([Liu et al., 2018](#)). For example, PLA degrades into lactic acid, which is metabolized via the tricarboxylic acid cycle, whereas PCL undergoes slower enzymatic cleavage by lipases and esterases due to its hydrophobic nature. PBS and PBAT exhibit intermediate degradation rates, with PBS

preferentially degraded by *Aspergillus* and *Fusarium* species in compost environments ([Rydz et al., 2014](#)). Despite their advantages, challenges persist in balancing mechanical performance and degradation rates. For instance, PLA's brittleness limits its use in flexible packaging, necessitating plasticizers or blending with PCL or PBAT to improve toughness ([Marasinghe et al., 2024](#)).

Recent advances in polymer engineering have focused on optimizing aliphatic polyester properties through structural modifications. Star-shaped PLA architectures, synthesized via ring-opening polymerization, a process explained in detail later in the chapter, with multifunctional initiators, enhance tensile strength and reduce brittleness by distributing stress more evenly across branched chains ([Sharma & Satapathy, 2019](#)). Similarly, incorporating PBS into PLA matrices improves thermal stability and impact resistance, as demonstrated in food packaging applications ([Stepanova & Korzhikova-Vlakh, 2022](#)). The integration of nanofillers, such as cellulose nanocrystals or montmorillonite clay, further enhances barrier properties against oxygen and moisture, addressing limitations in high-humidity environments ([Marasinghe et al., 2024](#)).

3.2.2 Physical and Mechanical Properties

Aliphatic polyesters exhibit a wide range of physical and mechanical properties, which can be tailored through variations in composition, molecular weight, crystallinity, and processing techniques. These properties include tensile strength, Young's modulus, elongation at break (EAB), and barrier performance. Their versatility makes them suitable for applications in packaging, biomedical devices, and structural materials.

The tensile strength and Young's modulus of aliphatic polyesters are largely determined by their molecular structure and degree of crystallinity. For instance, polylactide (PLA) exhibits high tensile strength (50–70 MPa) and Young's modulus of 3–4 GPa due to its semicrystalline nature and rigid backbone structure. These properties make PLA a strong candidate for rigid packaging applications ([Sharma & Satapathy, 2019](#)). In contrast, polycaprolactone (PCL), with its long aliphatic chains and low crystallinity, demonstrates lower tensile strength (15–20 MPa) but greater flexibility, making it suitable for applications requiring elasticity ([Liu et al., 2018](#)). Polybutylene succinate (PBS), another aliphatic polyester, exhibits intermediate tensile strength (30–40 MPa) and Young's modulus of approximately 1 GPa, offering a balance between stiffness and ductility for use in agricultural films and disposable items ([Rydz et al., 2014](#)). The elongation at break is a critical parameter for assessing

the flexibility of aliphatic polyesters. PCL is particularly notable for its high EAB, often exceeding 400%, due to its flexible methylene-rich backbone. This property contrasts with PLA, which has an EAB of less than 10%, reflecting its brittleness. For example, Sharma and Satapathy demonstrated that PLA/PCL composite patches with 80 wt% PCL content exhibited superior ductility while maintaining adequate tensile strength ([Sharma & Satapathy, 2019](#)). Similarly, PBAT, with an EAB exceeding 500%, is widely used in flexible films and compostable bags due to its exceptional stretchability combined with biodegradability ([Stepanova & Korzhikova-Vlakh, 2022](#)).

Aliphatic polyesters generally exhibit hydrophobic surfaces due to their non-polar aliphatic chains. While this hydrophobicity enhances their barrier properties against water vapor and gases like oxygen and carbon dioxide, which are essential for food packaging, it can limit cell adhesion in biomedical applications. Surface modification techniques, such as plasma treatment or chemical grafting of hydrophilic groups, have been employed to improve biocompatibility and cell affinity ([Bu et al., 2019](#)). For instance, plasma treatment introduces charged groups onto the surface of PLA or PCL scaffolds, enhancing protein adsorption and cellular attachment in tissue engineering applications ([Miele et al., 2020](#)).

The mechanical properties of aliphatic polyesters can be further improved through copolymerization or blending strategies. For instance, blending PLA with PBS enhances impact resistance while maintaining biodegradability. A study by Cai et al. used Camellia seed powder to form better blends of PLA/PBS. The results showed that at 30 parts of CSP, the strength of the blend increased by 44%, and stretchability increased by 150% ([Cai et al., 2023](#)). Another study used succinic anhydride to mix PLA with PLB and stretched it in multiple directions, which made the films tougher and increased the impact resistance by 80–90 times ([Jariyasakoolroj et al., 2024](#)). Similarly, copolymerizing PLA with glycolide to form poly(lactide-co-glycolide) (PLGA) reduces brittleness by disrupting crystallinity while fine-tuning degradation rates from six months down to two months for biomedical applications such as drug delivery systems ([Z. Yang et al., 2024](#)). Nanocomposites incorporating cellulose nanocrystals or graphene oxide have also been explored to enhance the tensile strength and thermal stability of PLA-based materials while improving their barrier properties against oxygen and moisture ([Stepanova & Korzhikova-Vlakh, 2022](#)).

3.2.3 Thermal Properties

The thermal properties of aliphatic polyesters are critical for their processing, application, and performance in various industries, including packaging, biomedical devices, and textiles. The main properties mentioned in this section are glass transition temperature (T_g), melting temperature (T_m), thermal stability, and cold crystallization behavior, which are highly dependent on the polymer's molecular structure, crystallinity, and composition ([Olejnik et al., 2020](#)). The T_g of aliphatic polyesters reflects the temperature at which the polymer transitions from a rigid glassy state to a more flexible rubbery state. This parameter is influenced by the polymer's backbone rigidity and side-chain structure. For instance, polylactic acid (PLA) typically exhibits a T_g in the range of 55–60°C due to its semicrystalline nature and relatively rigid backbone ([Olejnik et al., 2020](#)). In contrast, polycaprolactone (PCL), with its long methylene segments, has a much lower T_g of approximately –60°C, making it highly flexible even at low temperatures ([Chatani et al., 1992](#)). Polybutylene succinate (PBS) and poly(butylene adipate-co-terephthalate) (PBAT) exhibit intermediate T_g values around –30°C and –20°C, respectively, due to their aliphatic chains combined with some structural rigidity from aromatic components in PBAT ([Rydz et al., 2014](#)).

The T_m of aliphatic polyesters is another critical thermal property that defines their processing window and crystalline behavior. PLA typically melts between 145°C and 160°C, depending on its stereochemistry and degree of crystallinity. For example, highly crystalline poly(L-lactic acid) (PLLA) exhibits a higher T_m , whereas amorphous poly(DL-lactic acid) (PDLLA) lacks a distinct melting point ([Olejnik et al., 2020](#)). PCL has a significantly lower T_m of approximately 60°C due to its flexible chain structure and reduced intermolecular interactions ([Bhadran et al., 2023](#)). PBS exhibits a T_m around 90–120°C depending on its molecular weight and crystallinity, while PBAT lacks a sharp melting point due to its copolymeric nature but softens around 110–120°C ([Stepanova & Korzhikova-Vlakh, 2022](#)).

The thermal stability of aliphatic polyesters is crucial for their durability during processing and use. PLA generally begins to thermally degrade at temperatures above 200°C through depolymerization into lactide monomers or chain scission reactions. However, its thermal stability can be enhanced through blending or the incorporation of stabilizing agents. For example, the addition of natural antioxidants such as flavone or trans-chalcone has been shown to increase the oxidation temperature of PLA/poly(3-hydroxybutyrate) blends from 233°C to 241°C and 232°C to 269°C, respectively, by scavenging free radicals generated during thermal degradation ([Olejnik et al., 2020](#)). Hallstein et al. conducted another research on improving the thermal stability of PLA using a new stabilizer from aziridine compounds and an acid

scavenger. As a result, PLA stayed intact for 850–1,200 hours compared to the old commercial stabilizers like polymeric carbamides, which degraded in hot water in 300 hours ([Hallstein et al., 2024](#)). PLA exhibits superior thermal stability compared to PLA due to its lower crystallinity and slower degradation kinetics under oxidative conditions. PBS and PBAT also demonstrate good thermal stability, with degradation onset temperatures typically above 250°C when properly stabilized with additives or through copolymerization strategies ([Rydz et al., 2014](#)).

Cold crystallization is a phenomenon observed in semicrystalline polymers that crystallize slowly upon cooling from the melt. This behavior is particularly prominent in PLA and other slow-crystallizing polyesters like poly(3-hydroxybutyrate) (P(3HB)). During reheating from the amorphous state below their T_m , these polymers undergo exothermic crystallization as molecular chains reorganize into ordered structures. The kinetics of cold crystallization are influenced by factors such as molecular weight, cooling rate, and the presence of nucleating agents or plasticizers. For example, metal oxide nanofillers have been shown to catalytically enhance the cold crystallization rate of PLA by reducing activation energy barriers for crystal nucleation and growth ([Stepanova & Korzhikova-Vlakh, 2022](#)). In conclusion, the thermal properties of aliphatic polyesters are highly versatile and can be tailored through compositional adjustments, blending strategies, or the incorporation of functional additives.

3.2.4 Environmental Impact

The potential derivation from renewable resources further mitigates the environmental impact of aliphatic polyesters. PLA, synthesized from cornstarch or sugarcane, and PBS, produced from bio-based succinic acid and 1,4-butanediol, significantly lower reliance on fossil fuels ([Rydz et al., 2014](#)). PBAT, though partially derived from petrochemicals, is useful for compostable films and agricultural mulches ([Marasinghe et al., 2024](#)). However, the sustainability of these polymers depends on end-of-life management. Industrial composting infrastructure is critical for PLA and PBAT to fully degrade, as inadequate facilities may lead to incomplete breakdown and microplastic formation ([Yu & Flury, 2024](#)).

In food packaging, aliphatic polyesters balance functionality and eco-friendliness. Despite the advantages, challenges persist. For instance, the hydrophobicity of PLA limits its use in high-moisture environments unless modified with hydrophilic additives or blended with polymers like PBS ([Marasinghe et al., 2024](#)). Innovations such as nanocellulose reinforcement or surface coatings have improved moisture

resistance, enhancing their practicality in humid conditions ([Samir et al., 2022](#)). The environmental benefits of aliphatic polyesters extend beyond waste reduction. Their production from renewable feedstocks lowers greenhouse gas emissions compared to petroleum-based plastics, aligning with circular economy principles ([Versino et al., 2023](#)). For example, compostable PBAT/TPS blends convert packaging waste into nutrient-rich soil amendments, supporting agricultural sustainability. Nevertheless, life cycle assessments highlight the need for optimized production processes and scaled composting infrastructure to maximize their ecological advantages ([Yu & Flury, 2024](#)).

Aliphatic polyesters represent a transformative shift toward sustainable materials, offering reduced environmental impact through renewable sourcing. While challenges in processing, cost, and degradation management remain, research and policy support are critical to realizing their full potential in mitigating plastic pollution and advancing global sustainability goals ([Asri et al., 2024](#)).

3.3 TYPES OF ALIPHATIC POLYESTERS IN FOOD PACKAGING

The most prominent types include polylactic acid (PLA), polycaprolactone (PCL), polybutylene succinate (PBS), poly(butylene adipate-co-terephthalate) (PBAT), and polyhydroxyalkanoates (PHAs).

3.3.1 Polylactic Acid (PLA)

Polylactic acid (PLA) is a leading biodegradable polyester derived from renewable resources such as cornstarch, sugarcane, and cassava, synthesized via microbial fermentation of lactic acid followed by polymerization ([Mustăţea et al., 2019](#); [De Luca et al., 2023](#)). Its prominence in food packaging stems from its transparency, processability, and moderate barrier properties against oxygen (O₂) and carbon dioxide (CO₂), which are critical for preserving perishable foods like fruits, vegetables, and dairy products ([Shao et al., 2022](#)). However, inherent limitations such as brittleness and poor moisture resistance restrict its standalone use in high-humidity environments or applications requiring mechanical flexibility.

To address these challenges, researchers have developed advanced PLA composites by blending them with plasticizers, reinforcing agents, and antibacterial

additives. Incorporating cellulose nanocrystals (CNC) shortens the crystallization half-time from 33.7 min for just PLA to 1.7 min for PLA/CNC composite, increasing crystallinity and creating tortuous diffusion pathways for gas molecules ([X. Zhang et al., 2018](#)). Similarly, PLA/polyhydroxybutyrate (PHB) at the ratio of 75:25 blended with 1% weight chitin nanocrystals (ChNCs) reduced OTR value by 4.8 times and 1.6 times compared to neat PLA and neat PHB, respectively, thus making it a great choice for food packaging ([Patel et al., 2022](#)). These modifications enable PLA-based films to meet the rigorous demands of flexible packaging, such as stretchable wraps for fresh produce or thermoformed trays for ready-to-eat meals. Antimicrobial functionality is another critical advancement in PLA packaging. Incorporating natural antibacterial agents like plant extracts, such as grapefruit seed extract or essential oils, into PLA matrices inhibits microbial growth, extending the shelf life of packaged foods such as bread and meat ([Shao et al., 2022](#)). For instance, solvent-cast PLA films infused with thymol or cinnamaldehyde demonstrate sustained release kinetics, effectively suppressing *E. coli* and *Staphylococcus aureus* over 14 days ([Ramos et al., 2020](#)). However, the dispersion of hydrophobic additives within the PLA matrix remains a challenge, often requiring compatibilizers like maleic anhydride or glycidyl methacrylate to ensure homogeneity and prevent phase separation ([Alikarami et al., 2022](#)).

Processing techniques further influence PLA's performance. Extruded PLA films exhibit superior barrier properties compared to solvent-cast variants due to enhanced polymer chain alignment and crystallinity. Innovations such as reactive extrusion with epoxidized soybean oil methyl ester (ESOME) as a plasticizer improve flexibility and oxygen barrier properties in PLA/PHB blends, achieving a 30% reduction in oxygen transmission rate. These advancements position PLA as a versatile material for applications ranging from rigid containers for yogurt and beverages to compostable cutlery and agricultural films ([Mustățea et al., 2019](#)).

3.3.2 Polycaprolactone (PCL)

Polycaprolactone (PCL), a biodegradable aliphatic polyester synthesized via ring-opening polymerization of ϵ -caprolactone, has gained prominence in food packaging due to its exceptional flexibility, where its elongation at break is greater than 400%, low melting point of around 60°C, and compatibility with hydrophilic biopolymers. PCL's semicrystalline structure, characterized by a glass transition temperature of -60°C and a density of 1.07–1.2 g·cm⁻³, provides mechanical resilience comparable to conventional plastics ([Oney-Montalvo et al., 2024](#)). However, its slow degradation

rate in ambient environments limits its utility to applications requiring controlled biodegradation timelines, such as short-term food packaging or agricultural mulches ([Thakur et al., 2023](#)). PCL's versatility is enhanced through blending with natural polymers like chitosan or starch, which improve hydrophilicity and functional performance. Studies demonstrate that grapefruit extract (GSE)-loaded PCL films achieve a 5.8-log reduction in bacterial counts, extending the shelf life of perishable foods such as bread and cheese by inhibiting microbial growth while maintaining structural integrity during storage ([Lyu et al., 2019](#)).

In meat packaging, PCL films modified with antimicrobial agents such as propolis extract combined with chitosan coating enriched with an essential oil called *Zataria multiflora* have been shown to increase the shelf life of chicken breast by around 16 days ([Oney-Montalvo et al., 2024](#)). Similarly, PCL-based microcapsules encapsulating organic acids or polyphenols are integrated into dairy product packaging to slow spoilage while ensuring controlled release of active compounds ([Oney-Montalvo et al., 2024](#)). Despite these advancements, challenges persist in optimizing PCL's thermal stability and moisture resistance. Biodegradation studies of PCL films via soil burial tests reveal a weight loss of approximately 30% over 60 days, attributed to enzymatic cleavage of ester bonds by microbial depolymerase ([Zampolli et al., 2024](#)). While this degradation rate is slower than that of PLA or PHAs, it aligns with the requirements for medium-term packaging applications. Future research focuses on accelerating PCL's biodegradation through copolymerization with hydrophilic monomers or the addition of pro-oxidants, ensuring compatibility with circular economy principles ([Oney-Montalvo et al., 2024](#)).

3.3.3 Polybutylene Succinate (PBS)

Polybutylene succinate (PBS), a biodegradable aliphatic polyester synthesized via polycondensation of bio-based succinic acid and 1,4-butanediol, has emerged as a versatile material for food packaging due to its balanced mechanical properties, thermal stability, and biodegradability ([Nabels-Sneiders et al., 2023](#)). PBS is used in applications requiring moderate thermal resistance, such as hot food containers and microwave-safe packaging, as well as for rigid packaging, agricultural mulch films, and flushable hygiene products ([Righetti et al., 2022](#)). The mechanical performance of PBS is further enhanced through copolymerization and composite strategies. Additionally, blending PBS with polylactic acid (PLA) creates materials that combine PLA's rigidity with PBS's ductility, achieving a tensile strength of ~35 MPa

and elongation at a break of ~200% in PBS/PLA (70/30) blends. However, PBS's hydrophobicity and moderate moisture resistance pose challenges in high-humidity environments. To address this, layered PBS films incorporating nanofibrillated cellulose (NFC) derived from hemp stalk waste reduce water vapor transmission rates (WVTR) by up to 5.5-fold, even with a minimal NFC content of 0.35%. These laminates retain biodegradability while offering improved barrier properties for perishable foods like meats and baked goods.

Thermal degradation studies reveal that PBS decomposes primarily at 399–404°C, with thermal stability influenced by additives such as thermoplastic starch (TPS) and bioactive agents. For example, PBS/TPS composites modified with bamboo microparticles (BM) exhibit enhanced thermal stability, delaying decomposition to ~483°C while maintaining biodegradability under composting conditions ([Nabels-Sneiders et al., 2023](#)). However, hydrothermal aging studies demonstrate that PBS/NFC composites experience reduced crystallinity and adhesion efficiency over time, necessitating optimization of NFC loading (≤ 20 wt.%) to balance mechanical reinforcement and environmental durability.

In food packaging, PBS's non-toxicity and processability via blow molding or extrusion enable its use in thermoformed trays, squeeze pouches, and biodegradable cutlery. Innovations such as spray-coated nanofibrillated cellulose (NFC) interlayers in PBS films not only improve WVTR but also provide UV protection, extending shelf life for light-sensitive products like oils and dairy. NFC is a natural fiber made from hemp waste, and even just adding 1 thin layer of NFC made the packaging water vapor resistant 5.5 times; however, too many layers (10) make it weaker and reduce the visibility of packaging material from 65% to 25% ([Nabels-Sneiders et al., 2023](#)). Despite its advantages, PBS's higher cost compared to conventional plastics like polypropylene (PP) remains a barrier to widespread adoption. Ongoing research focuses on scaling bio-based succinic acid production and optimizing composite formulations to enhance cost-effectiveness without compromising performance ([Nabels-Sneiders et al., 2023](#)).

3.3.4 Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs), a class of microbial polyesters biosynthesized by bacterial fermentation of renewable feedstocks, have emerged as promising candidates for sustainable food packaging due to their superior barrier properties against moisture and gases, biodegradability, and versatility. PHA, such as polyhydroxybutyrate (PHB) and poly(hydroxybutyrate-co-valerate) (PHBV), exhibit

hydrophobic characteristics that confer excellent water vapor barrier performance, with water vapor transmission rates (WVTR) comparable to polyethylene terephthalate (PET), while their oxygen and carbon dioxide barrier properties are suitable for preserving perishable foods ([Atarés et al., 2024](#); [Singh et al., 2015](#)). Recent advancements in functionalizing PHAs with natural additives have expanded their utility in active packaging. For instance, PHBV films incorporating tannins exhibit multifunctional capabilities, including UV-blocking activity (90% UV-A and UV-B attenuation), antioxidant properties (80% DPPH radical scavenging), and colorimetric detection of ammonia vapors, enabling real-time spoilage monitoring for protein-rich foods like fish and poultry. These innovations position PHAs as “smart” packaging materials capable of extending shelf life while providing consumers with visual indicators of food safety ([Ferri et al., 2023](#)).

Despite their advantages, PHAs face significant challenges in industrial scalability and cost-effectiveness. Production costs remain high due to energy-intensive fermentation and downstream purification processes, with PHAs costing approximately two to five times more than conventional plastics like polypropylene ([Atarés et al., 2024](#)). To mitigate these challenges, blending PHAs with other biopolymers such as polylactic acid (PLA) or poly(butylene adipate-co-terephthalate) (PBAT) has been explored. For example, PHB/PLA blends reduce material costs by up to 30% while maintaining barrier properties. PHBV/PBAT composites enhance flexibility and thermal stability, making them suitable for thermoformed food trays and stretchable films. However, the immiscibility of PHA blends often necessitates compatibilizers like maleic anhydride or reactive extrusion techniques to optimize interfacial adhesion and mechanical performance. Biodegradation kinetics further influence PHA applications. Under industrial composting conditions, PHAs degrade within 6–12 weeks via enzymatic hydrolysis of ester bonds, whereas anaerobic digestion in marine environments achieves 90% mineralization within 10 weeks, significantly outperforming PLA, which persists in aquatic systems ([Atarés et al., 2024](#)). Nevertheless, inconsistent composting infrastructure globally limits its practical biodegradability, necessitating policy interventions to standardize waste management systems.

Future research priorities include optimizing microbial strains for higher PHA yields, developing cost-effective carbon sources like agricultural waste, and advancing reactive blending technologies to enhance compatibility in multicomponent systems ([Atarés et al., 2024](#)). With continued innovation, PHAs hold transformative potential to replace conventional plastics, aligning food packaging with circular economy principles.

3.4 SYNTHESIS AND PRODUCTION METHODS

3.4.1 Raw Material and Sources

The synthesis of aliphatic polyesters still faces major challenges based on the availability of high-quality raw materials, which significantly influence their properties, production efficiency, and environmental impact when it comes to large-scale manufacturing. Polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and polybutylene succinate (PBS), which hold significant commercial and industrial values, are often synthesized from various bio-based raw materials that are primarily derived from microbial sources, plant oils, and sugars.

Lactic acid, the cornerstone of PLA, is derived from batch fermentation of carbohydrates like glucose and sucrose, usually extracted from cornstarch, and sugarcane serves as its primary feedstock. This process relies on lactic acid bacteria, such as *Lactobacillus*, which churn out the high-purity lactic acid ready for polymerization at incubated conditions ([Zhao et al., 2023](#)). Industrially, large-scale lactic acid is sourced from the fermentation or chemical synthesis of natural resources such as coal, petroleum, and natural gas. Depending on the application, lactic acid can be produced at different purity levels. [Figure 3.2](#) shows the chemical synthesis and microbial fermentation to manufacture lactic acids, along with the formation of different lactides. The first route involves microbial fermentation, starting with renewable sources undergoing saccharification and fermentation processes in low oxygen and low pH environment at 40°C for three to five days, producing a fermented broth. This broth can yield either L-lactic acid or D-lactic acid, which are subsequently purified for food packaging applications, using recycled ammonia (NH₃) or sodium hydroxide (NaOH) to achieve high purity (>99.5%). The second route involves chemical synthesis using resources derived from petroleum or coal. In this pathway, acetaldehyde reacts with hydrogen cyanide (HCN) in the presence of a catalyst to form lactonitrile. This intermediate undergoes hydrolysis using sulfuric acid (H₂SO₄), resulting in D, L-lactide with a purity level typically above 99% ([Ramezani Dana & Ebrahimi, 2023](#)). Although chemical methods enable large-scale continuous production of lactic acid and have received approval from the U.S. Food and Drug Administration (FDA), the raw materials used are typically toxic and do not comply with green chemistry principles. Hence, recent research has demonstrated an alternative approach involving simultaneous saccharification and fermentation by incorporating bacteria and substrate-degrading enzymes to convert

starch or cellulosic biomass directly into lactic acid by potentially replacing the conventional fermentation method. This integrated approach effectively reduces production costs and enhances overall process efficiency ([Li et al., 2020](#)).

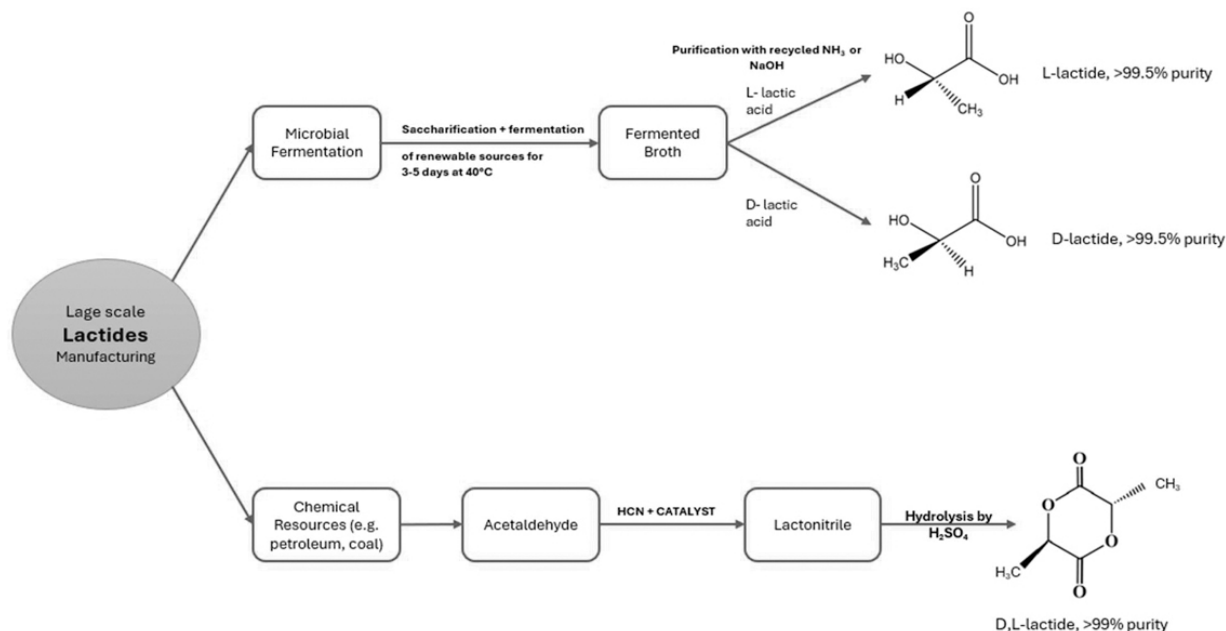


FIGURE 3.2 Schematic representation of large-scale lactide manufacturing illustrating two main synthetic routes: microbial fermentation of renewable sources and chemical synthesis from petroleum-based resources. ↵

Microbial polymers, PHAs, are spontaneously synthesized by over 300 different gram-positive and gram-negative bacteria, fungi, yeast, and algae in high concentrations of carbon and energy reserves under nutrient-deficient conditions in the cytoplasm of microbial organisms. Bacteria, being the most common microorganism where this synthesis occurs, can be sub-divided into two groups depending on the stress conditions required for the PHA synthesis—the first group of bacteria lacks essential nutrients such as nitrogen, magnesium, or sulfur with an excess carbon source during the stationary phase of fermentation, such as *Ralstonia eutropha* and *Pseudomonas putida*. The second group of bacteria does not require such harsh nutrient-deficient conditions to synthesize PHAs, which often occurs during the growth phase, such as *Alcaligenes Latus* and *Escherichia coli* ([Anjum et al., 2016](#); [Zytner et al., 2023](#)). An expanding body of research is focusing on the implementation of recombinant or genetically modified bacteria for the fermentation process. *E. coli* is often selected for these studies as it grows fast, even at higher temperatures, and so it is easy to modify and has strong potential for broad industrial application genetically. PHAs' ability to biodegrade in soil, compost, or water

without leaving any toxic residue has made them a potential replacement for synthetic polymers throughout various industries, particularly in food packaging and other single-use products ([Zytner et al., 2023](#)).

However, the use of costly and non-renewable carbon sources has limited the industrial-scale production of PHA compared to conventional plastics. Moreover, relying on first-generation sugar-based cultivated feedstocks, such as food crops, whey, sugarcane, and vegetable oils, for PHA production raises concerns about food security for the rapidly growing population and demands substantial resources, including land and energy. Over the years, significant efforts have been directed toward identifying sustainable and economically viable carbon sources to reduce the overall cost of PHA production. A recent study involves utilizing second-generation plant waste lignocellulosic feedstocks (LF) such as maize stalks, rice straws, or forestry byproducts like wood chips ([Vigneswari et al., 2021](#)).

Polybutylene succinate (PBS) is a class of biodegradable aliphatic polyester that can be achieved from monomers of succinic acid and 1,4-butanediol (BDO) that can be derived from either fossil-based or renewable resources. Succinic acid is industrially produced via chemical routes, such as petroleum-based feedstocks. Common industrial methods include paraffin oxidation, catalytic hydrogenation, or electroreduction of maleic anhydride or maleic acids. Additionally, succinic acid can also be produced more sustainably through bacterial fermentation of renewable feedstocks such as glucose, xylose, starch, food waste, crop residues, and wheat milling by-products. Various bacterial strains such as *Actinobacillus succinogenes*, *Anaerobiospirillum succiniciproducens*, and recombinant *Escherichia Coli* are widely used to produce succinic acid by fermenting feedstocks. Recent advances in research have shown that a genetically modified bacterial strain (*Corynebacterium glutamicum*) has the potential to have higher efficiency in the production of succinic acid. The second most common raw material, BDO, which is also an organic compound used for PBS synthesis, can be industrially manufactured from fossil resources, such as through the hydrogenation of maleic anhydride, which is an intermediate of maleic acid, which can be derived from oxidation of butane or benzene. BDO can also be produced using sustainable bio-based processes by using renewable feedstock to ferment into succinic acid, which is subsequently purified and catalytically reduced to BDO. Alternative bio-based methods also include direct fermentation of sugars by microorganisms ([Barletta et al., 2022](#)).

3.4.2 Polymerization Techniques

The polymerization of aliphatic polyesters involves both chemical and biotechnological approaches. For PLA, two primary methods are polymerization through lactide formation and direct condensation polymerization of lactic acid. In the lactide route, lactic acid oligomers undergo esterification to form lactide, which is then polymerized through ring-opening to create PLA with controlled molecular weights, ideal for industrial use. However, the use of traditional catalysts in this process can limit applications, especially in food packaging, prompting the development of non-toxic and enzyme-based catalysts. The direct condensation method, while simpler and cost-effective, often produces lower molecular weight PLA due to challenges in water removal during polymerization. Advances like azeotropic condensation and melt-solid polymerization have helped address this issue, enabling higher molecular weights ([Zhao et al., 2023](#)). Beyond chemical methods, microbial synthesis offers a sustainable alternative for producing bioplastics like PHAs formed through enzymatic polymerization rather than traditional chemical polycondensation methods. This kind of synthesis occurs intracellularly, mostly in the cytoplasm of bacteria, which acts as a method of carbon and energy storage and involves enzyme-mediated processes rather than external catalysts. The key polymerization methods used during the synthesis of PHAs mainly include microbial fermentation-based synthesis, followed by specific metabolic pathways to polymerize PHAs intracellularly. Three major polymerization routes are involved. Pathway I converts substrates into acetyl-CoA, followed by enzymatic reactions involving β -ketoacyl-CoA thiolase (PhaA), acetoacetyl-CoA reductase (PhaB), and PHA synthase (PhaC_{scl}) to form poly(3-hydroxybutyrate) (PHB) to produce short-chain-length PHAs. Pathway II is responsible for synthesizing medium-chain-length PHAs through the β -oxidation of fatty acids into R-3-hydroxyacyl-CoA, which is then further polymerized by the enzyme PhaC_{mcl}. Pathway III, which is the final polymerization route, utilizes either R-3-hydroxyacyl-ACP from fatty acid biosynthesis or R-3-hydroxyacyl-CoA from β -oxidation, mediated by the enzyme PhaG and subsequent polymerization by PHA synthase. These pathways aid different PHA monomer incorporation, offering flexibility in polymer structure and properties. Recent advancements have also focused on utilizing recombinant strains like modified *E. coli* that are engineered for enhanced polymerization to modify metabolic fluxes and introduce new PHA biosynthesis genes. These modifications significantly improve polymer yield, molecular weight control, and monomer composition. [Figure 3.3](#) is a circular schematic that shows the sustainable production and lifecycle of polyhydroxyalkanoates (PHAs) from waste lignocellulosic biomass. This lifecycle describes how waste lignocellulosic biomass is converted into PHAs

through pretreatment and fermentation. After use, PHAs have the potential to biodegrade in composting facilities that eventually enrich soil fertilization and support new biomass growth. Even if improperly discarded, their universal biodegradability reduces environmental harm, offering sustainable green chemistry ([Zytner et al., 2023](#)).

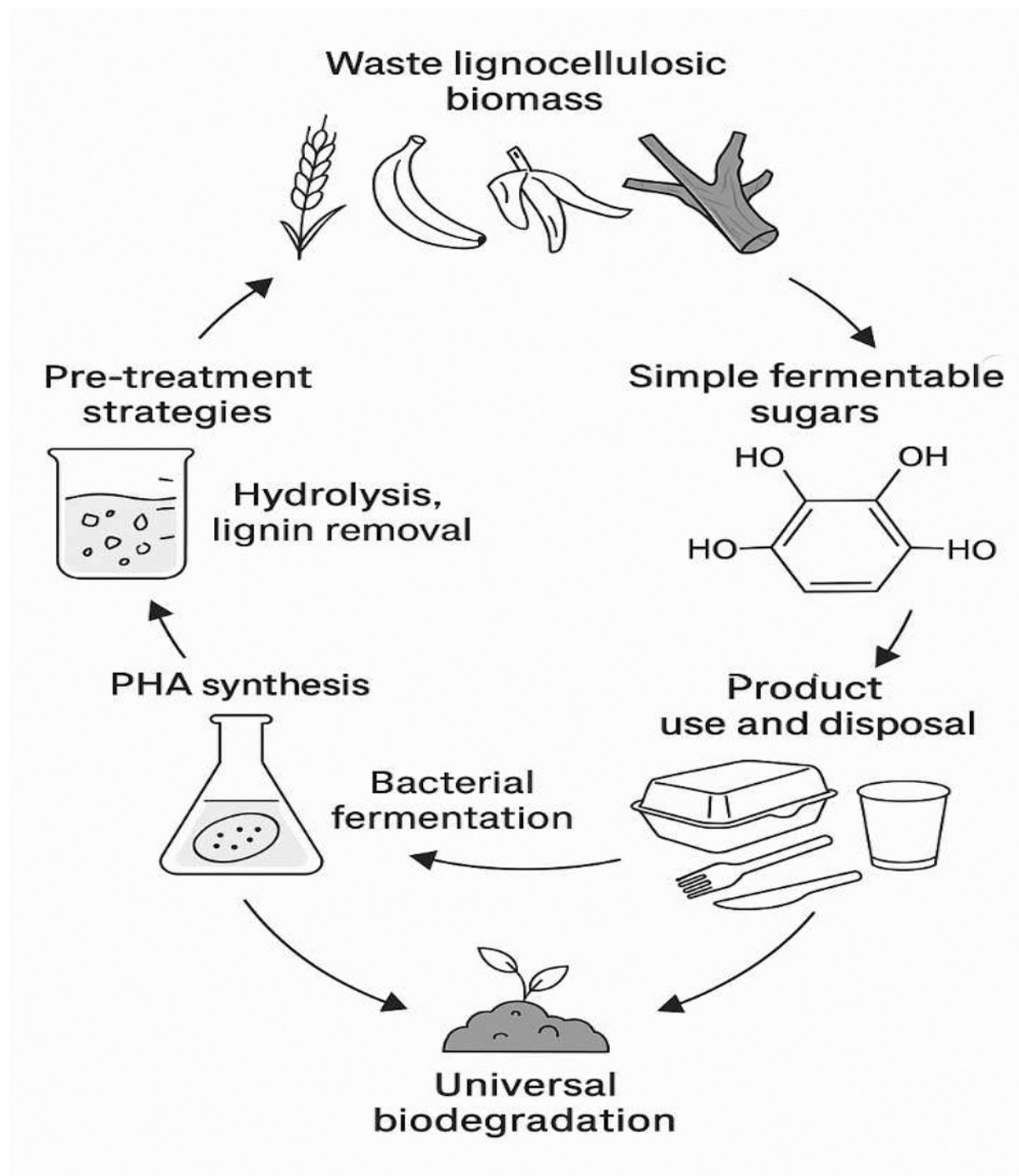
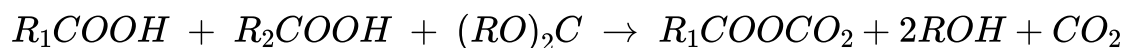


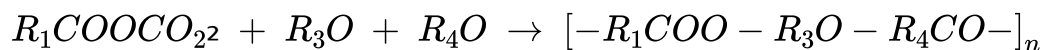
FIGURE 3.3 Circular schematic illustrates the sustainable production and lifecycle of polyhydroxyalkanoates (PHAs) from waste lignocellulosic biomass. [↗](#)

PBS is commercially synthesized via copolymerization along with polycondensation using different types and ratios of co-monomers of succinic acid and 1,4-butanediol. Furthermore, PBS can be modified via copolymerization with other dicarboxylic acids or diols to make it suitable for a wider range of practical applications, such as food packaging or materials for biomedical devices. The pre-polymer formation includes two major steps: esterification reaction, where succinic acid reacts with BDO at a high temperature of 170–190°C for a well-established time range without any presence of a catalyst, and transesterification, where dimethyl succinate reacts with BDO to form PBS oligomers, which occurs under controlled heating (160–190°C) in an inert nitrogen atmosphere, followed by further heating (220–240°C) under vacuum and in presence of various metal-based catalysts. These steps typically produce water or methanol as a byproduct, offering a green residue ([Barletta et al., 2022](#)). Emerging tandem catalysis techniques further streamline biodegradable polymer production by combining cyclic anhydride formation and their copolymerization with epoxides in a single system as traditional methods, like polycondensation and ring-opening polymerization, often face challenges such as high energy demands and limited polymer architectures. An example of cyclization and copolymerization reactions of the polyester derived from epoxides and carboxylic acids can look like the following:

Step 1: Cyclization Reaction



Step 2: Copolymerization Reaction



The cyclization step converts dicarboxylic acids into cyclic anhydrides efficiently under mild conditions, avoiding complex purification steps. These anhydrides are then directly copolymerized with epoxides to produce alternating polyesters. The tandem approach not only simplifies the production process but also enhances catalyst utilization by enabling multiple catalytic cycles with a single catalyst. This method has shown great promise for yielding biodegradable polyesters with precise molecular weights and narrow molecular weight distributions. [Table 3.1](#) describes

different types of plastics based on various characteristics. It distinguishes between fossil-based and bio-based polymers, further dividing bio-based types into biodegradable and non-biodegradable categories. Examples of common polymers are listed for each group, along with their durability characteristics, ranging from highly durable to hydrolysis-susceptible.

Polymerization is vital for synthesizing aliphatic polyesters, and selecting the right technique is crucial to achieving the desired properties for specific food packaging applications. The two primary methods for synthesizing aliphatic polyesters are polycondensation and ring-opening polymerization (ROP), both of which have unique strengths and challenges.

TABLE 3.1 Classification of Plastics Based on Source, Durability, and Polymerization (Rosenboom et al., 2022) ↵

CATEGORY	DURABILITY	EXAMPLES OF POLYMERS	METHOD OF POLYMERIZATION	SOURCE
FOSSIL-BASED	Durable, non-biodegradable	PVC (polyvinyl chloride), PE (polyethylene), PP (polypropylene)	Free-radical or step-growth polymerization from fossil fuels	Derived from petroleum
Bio-Based	Durable, non-biodegradable	BioPCs (polycarbonates), bioPUs (polyurethanes), bioPET, PEF (polyethylene furanoate)	Chemical polymerization from bio-derived monomers	Biomass (corn, sugarcane)
Biodegradable	Largely Susceptible to Hydrolysis	PLA (polylactic acid), PBS (bio-based polybutylene succinate), PHAs (polyhydroxyalkanoates)	Ring-opening or condensation polymerization; microbial biosynthesis	Renewable resources (feedstocks, microorganisms, starch, oil)

CATEGORY	DURABILITY	EXAMPLES OF POLYMERS	METHOD OF POLYMERIZATION	SOURCE
Biologically Extracted	Biodegradable	Starch, cellulose	Physical or chemical extraction; no synthetic polymerization occurs	Plants, fungi

3.4.2.1 Ring-Opening Polymerization (ROP) of Aliphatic Polyesters

Ring-opening polymerization (ROP) is a very well-known method that is commonly used for synthesizing aliphatic polyesters, offering precise control over molecular weight, composition, and polymer architecture. ROP proceeds under milder conditions and avoids equilibrium limitations, making it ideal for producing high-performance biodegradable polyesters like PLA and poly(ϵ -caprolactone) (PCL) ([Bednarek, 2016](#); [Jérôme & Lecomte, 2008](#)). ROP typically involves the polymerization of cyclic monomers such as lactides, ϵ -caprolactone, and glycosides. Two main mechanisms govern the process:

Coordination-Insertion Mechanism: Catalyzed by organometallic compounds such as aluminum alkoxides or tin (II) octoate, this mechanism involves the coordination of the metal catalyst to the monomer's carbonyl group, followed by the insertion of the monomer into the growing polymer chain. This approach enables precise molecular weight control and narrow polydispersity ([Jérôme & Lecomte, 2008](#)).

Nucleophilic Initiation: In this mechanism, nucleophiles like alcohol or water initiate polymerization. This method is often used when less toxic initiators are needed, particularly for biomedical applications ([Bednarek, 2016](#)).

ROP offers several benefits, including the ability to produce high-molecular-weight polymers with narrow molecular weight distributions under mild reaction conditions, which are beneficial for applications such as tissue engineering, which is out of the scope of this chapter. However, using metal-based catalysts can leave toxic residues, limiting the polymers' applicability in sensitive areas like food packaging and biomedicine. To address this, researchers are continuously exploring alternative catalysts, such as enzymatic systems and fully organic initiators, which provide a

safer and greener route to polyester production ([Bednarek, 2016](#); [Jérôme & Lecomte, 2008](#)). [Table 3.2](#) illustrates the various polymer structures achievable through ROP, highlighting the combinations of monomers, catalysts, and resulting architectures. For example, hyperbranched polymers can be synthesized using AB₂ monomers with ROP catalysts, while graft polymers require the copolymerization of linear polymers with cyclic esters. This table serves as a concise summary of the relationships between polymerization mechanisms and resultant structures, reinforcing the concepts discussed ([Bednarek, 2016](#)).

TABLE 3.2 Summary of Polymer Architectures Produced via Ring-Opening Polymerization (ROP) with Different Catalysts and Reactants ([Bednarek, 2016](#)) 

REACTANTS	CATALYST	RESULTING STRUCTURE	REFERENCES
AB ₂	ROP Catalyst	Hyperbranched structure	(Sunder et al., 1999)
AB and AB ₂	ROP Catalyst	Diluted branching	
AB ₂ + AB	ROP Catalyst I and Polycondensation Catalyst II	Long-chain branches	(Huang & Onyari, 1996)
AB ₂ + AB	Combined ROP and Polycondensation Catalyst	Long-chain branches	(Zhu et al., 2007)
AB ₂ + Polyfunctional Alcohol Core	ROP Catalyst	Dendrimer-like star structure	(Srivastava et al., 2007)
Cyclic Ester or AB ₂ Monomer	ROP Catalyst	Core-shell structure	(Srivastava et al., 2007)
Linear Polymer + Cyclic Ester	ROP Catalyst	Grafted polymer structure	(Kiehl et al., 2012)

On the other hand, plant-based polyesters have a slightly different synthesis process through acyclic diene metathesis (ADMET) polymerization, followed by hydrogenation. This is a favorable method due to its wide scope of polymerization, especially in the polymer main chain. ADMET polymerization involves using a molybdenum-alkylidene catalyst to polymerize monomers like bis(undec-10-enoate)

with bio-based diol groups such as isosorbide, propanediol, and isomannide. This ring-opening catalytic polymerization has shown a reverse relationship as the molecular weight of the plant-based aliphatic polyesters increases with a decreasing catalyst concentration. However, one of the challenges of this ROP polymerization is the production of the by-product ethylene, which is crucial to remove for the synthesis of higher molar mass polymers as ethylene increases viscosity. Following the ADMET polymerization, the polymers are then hydrogenated to improve their tensile properties by using a rhodium-based complex $\text{RhCl}(\text{PPh}_3)_3$ in a hydrogen atmosphere to add across double bonds in the target molecule, converting it to a more saturated product. This process does not significantly increase the molecular weight of the polyesters ([Kojima et al., 2023](#)).

Some of the recent advancements in ROP include the use of supercritical carbon dioxide (scCO_2) as a reaction medium. This method not only facilitates polymerization but also allows for the purification of the resulting polyesters without the need for harmful solvents ([Jérôme & Lecomte, 2008](#)). Furthermore, the development of macromolecular engineering techniques has enabled the production of polyesters with tailored properties, such as amphiphilicity and pH sensitivity, expanding their potential applications ([Bednarek, 2016](#)).

3.4.2.2 Polycondensation of Aliphatic Polyesters

Polycondensation is one of the most conventional methods used to synthesize aliphatic polyester. This process involves reacting diols with dicarboxylic acids to create long polymer chains, with water as a byproduct. This ability to accommodate a broad range of monomers makes it a versatile and cost-effective method in the field of food packaging. However, achieving high molecular weights requires specific conditions, including high temperatures, reduced pressure, and precise stoichiometric control to efficiently remove water from the reaction system ([Sokolsky-Papkov et al., 2011](#)). Recent advancements have addressed some of the challenges in polycondensation. For instance, catalysts like inorganic acids, such as phosphoric acid (H_3PO_4) or sulfuric acid (H_2SO_4), have been effectively utilized to produce high-molecular-weight polyesters under mild reaction conditions, such as discussed in the synthesis of the plant-based polyesters ([Sokolsky-Papkov et al., 2011](#); [Zhao et al., 2023](#)). In some cases, azeotropic water removal techniques using aromatic solvents or vacuum settings are applied to drive the reaction equilibrium toward polymer formation. However, these methods can sometimes promote undesirable side reactions, such as ether formation or cyclization, which limit chain growth. As a

recent advance, researchers have integrated monomers like ricin-oleic acid or castor oil into the polycondensation process to further expand the versatility as these fatty monomers can increase polymer flexibility and adjust degradation rates without significantly reducing molecular weight. This innovation has opened new possibilities for producing biodegradable materials tailored for medical and environmental applications ([Sokolsky-Papkov et al., 2011](#); [Zhao et al., 2023](#)).

Despite its challenges, polycondensation remains a cornerstone of aliphatic polyester synthesis thanks to its simplicity and adaptability.

3.4.3 Challenges in Sustainable Production

The push toward sustainable production of aliphatic polyester faces several challenges, ranging from raw material sourcing to economic viability and technological limitations. The major drawback lies in the expensive manufacturing of biodegradable plastics, which eventually makes them less competitive in the market.

3.4.3.1 Raw Material Limitations

Sourcing raw materials for synthesizing aliphatic polyesters ([Vigneswari et al., 2021](#)), especially biodegradable ones such as PLA, PHAs, and PBS, presents several challenges across the sustainability and economic dimensions. Many bio-based polymers, such as PLAs, are mostly synthesized from first-generation feedstocks such as starch and cellulose from sugarcane, which eventually raises the question of supply of food and material competition, which can threaten food security and inflation of raw materials costs. Supplying large-scale industrial bio-based feedstocks that are primarily agricultural products poses potential issues affecting the regional food supply ([Zhao et al., 2023](#)). On the other hand, second-generation feedstocks (e.g., lignocellulosic biomass from agricultural or forestry waste) are more sustainable, but they require complex pretreatment (such as hydrolysis) and include the utilization of expensive enzymes and catalysts to release fermentable sugars ([Vigneswari et al., 2021](#)). Furthermore, integrating other materials, such as chemical additives in biodegradable polymers to enhance their mechanical properties, can negatively impact the environment and human health ([M. Zhang et al., 2022](#)).

3.4.3.2 Energy-Intensive Processes

Traditional methods like direct condensation polymerization require high energy inputs to drive the reaction and remove water molecules, and the intense energy recycling processes can impact the environmental footprint scalability and can make

manufacturing on a large scale more costly. Polycondensation and ring-opening polymerization steps used in PLA and PBS synthesis require high temperatures that typically range from 160°C to 240°C in controlled industrial-scale reactors, and maintaining such conditions demands significant energy input. It has also been seen that to drive PBS polymerization to high molecular weights, systems often operate under vacuum or high pressure, increasing both energy demand and equipment complexity. Additional use of catalysts (such as tin, titanium, or rare-earth metal catalysts) during polymerization or pretreatment, as seen in the transesterification process during PBS synthesis, needs energy for activation, separation, or regeneration ([Barletta et al., 2022](#)). Even though the production of bioplastics requires 65% less energy than conventional polymers, which results in reduced greenhouse gas production, biopolymers still require energy for sourcing raw materials, which can lead to negative environmental impacts such as acidification and eutrophication ([M. Zhang et al., 2022](#)). Although advancements like azeotropic condensation and enzymatic catalysis are helping reduce energy requirements, these techniques are still not universally adopted due to cost barriers ([Chen & Patel, 2012](#)).

3.4.3.3 Cost and Economic Feasibility

The economic aspect of synthesizing aliphatic polyesters has an overall effect on sourcing raw materials as well as the production costs while ensuring scalability; hence, it can create a significant barrier to commercial adoption. Bio-based monomers such as lactic acid, succinic acid, and BDO are often more expensive than fossil-based resources as the bio-based monomers have to be first fermented or pre-treated and processed into polymer products. On top of that, many steps in the production of aliphatic polyesters—such as ROP, azeotropic polycondensation, or vacuum distillation also require more than usual energy input, specialized equipment, and skilled labor to operate the complex processes. Catalysts play a pivotal role in controlling polymerization efficiency, selectivity, and molecular weight, but the use of rare or expensive metal catalysts can significantly inflate production costs ([De Hoe et al., 2022](#)).

3.5 FUNCTIONALIZATION AND MODIFICATION OF ALIPHATIC POLYESTERS

3.5.1 Chemical Modification to Enhance Properties

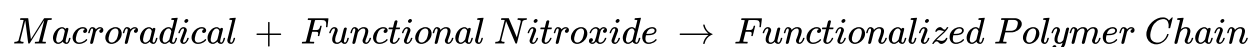
Over the years, several chemical modifications have been attempted to tailor the chemical properties of aliphatic polyesters to meet the diverse requirements of food packaging applications. While PLA and PHAs are biodegradable and environmentally friendly, their overall physical properties, such as brittleness, low barrier, and limited thermal stability, have been a challenge as they restrict their application in demanding food packaging scenarios. By employing chemical modification techniques, these limitations can be addressed, creating materials that combine sustainability with functionality. For example, PLA inherently suffers from low mechanical strength, brittleness, and poor interfacial bonding with natural fibers due to its low crystallinity (~10%); it can still enhance its physicochemical properties by reinforcing chemical modifications to improve its mechanical properties.

Plasticizers like 10% PBAT improve the flexibility, ductility, and processability of PLA composites, while compatibilizers such as triacetin can help strengthen the interface between PLA and fibers by improving fiber matrix bonding in PLA composites ([Ranakoti et al., 2022](#)). Further chemical modifications are discussed next, which are of high relevance and low cost.

3.5.1.1 Functionalization with Reactive Groups

Functionalization of aliphatic polyesters is a powerful approach to tailor their properties, making them suitable for diverse applications, including food packaging. One effective strategy is the introduction of functional reactive groups, also known as chain extenders (CE), into the polymer backbone or side chains to enhance properties like compatibility, barrier performance, and mechanical strength. Some examples of CE reactive groups are carboxylic groups, hydroxyl groups, and amine groups. These reactive molecules then react with the existing carboxylic groups in the polyesters. CEs can be bifunctional, where they form a linear chain extension to connect the two ends of the polyester, or multifunctional, where chain branching happens. This chemical modification occurs at high temperatures, during which polymers such as PLA tend to degrade through mechanisms like hydrolysis and depolymerization, resulting in reduced molecular weight. However, the use of chemical modifiers during reactive extrusion can benefit rebuilding the polymer chains by increasing molecular weight through chain extension, branching, or cross-linking. This complex process is influenced by factors such as modifier type and concentration, temperature, and reaction time and may also involve secondary reactions like transesterification or homo-polymerization ([Standau et al., 2019](#)).

A study achieved chemical modifications in the presence of free radicals such as nitroxide, introducing functional groups, such as benzoyloxy (BzO) or naphthoate (NfO) moieties, onto the polymer backbone. In food-safe applications, PBS and PLA have been successfully modified using this technique, preserving their biodegradable nature while imparting additional functionalities. These functionalized polymers exhibit enhanced adhesion properties, improving their integration during multi-layered packaging. A simple chemical reaction can be illustrated by the grafting of a functional nitroxide onto a polymer chain, forming a covalent bond that imparts functional properties to the polymer ([Cicogna et al., 2014](#)), as follows.



Another popular free radical that is extensively used for grafting is maleic anhydride in the presence of peroxide because of its good chemical reactivity, low toxicity, and lower potential for homo-polymerization to occur under free-radical grafting conditions. Free-radical-initiated grafting with maleic anhydride has been effectively used to enhance the viscosity and melt strength of polypropylene (PP). However, when applied to PLA, this kind of grafting tends to reduce molecular weight and viscosity. As a result, maleic anhydride grafting in PLA is primarily utilized as a compatibilizer in polymer blends. Notably, it enhances interfacial adhesion between PLA and starch through reactions between maleic anhydride and the hydroxyl groups present on the starch surface ([Standau et al., 2019](#)).

Introducing functional groups via surface modifications can also improve the water and gas barrier properties of aliphatic polyesters. For food packaging, these modifications aid in maintaining product freshness by reducing the moisture content and oxygen permeability. By grafting specific functional molecules onto PBS and PLA, their interaction with hydrophobic food materials can be tailored, providing better protection for the packaged goods ([Cicogna et al., 2014](#)).

3.5.1.2 Enhancing Barrier Properties

Food packaging requires materials that can adequately prevent the transmission of gases and moisture. Aliphatic polyesters like PLA typically exhibit higher oxygen permeability compared to conventional plastics. To address this limitation, incorporating nanomaterials such as cellulose nanocrystals (CNCs) into the polyester matrix has been shown to improve barrier properties. For instance, research has demonstrated that the inclusion of CNCs in PLA films significantly decreases water vapor and oxygen transmission rates, enhancing their suitability for food packaging.

applications ([Matuana, 2016](#)). Additionally, a more recent study established that PLA films exhibited higher water vapor permeability than the composite film containing 5 phr of curcumin, which is a natural hydrophobic polyphenolic compound, while its oxygen vapor permeability remained comparable up to the same concentration. This indicates that the addition of curcumin reduced water vapor permeability due to its hydrophobic nature, which limits vapor penetration and increases film tortuosity. The effective dispersion of curcumin within the PLA matrix via twin-screw extrusion further supports this observation. However, at higher curcumin concentrations (about 10 and 20 phr), the oxygen permeability increased due to reduced tortuosity. However, water vapor permeability remained stable up to 10 phr; higher curcumin content led to a decline in mechanical properties, which in turn increased vapor permeability in the resulting composite films ([Ranjeth Kumar Reddy & Kim, 2019](#)).

3.5.2 Blending and Composites

For decades, blending and composite formation have been the most commonly used strategies in enhancing the functional properties of aliphatic polyesters for food packaging applications. By integrating aliphatic polyesters with other polymers or reinforcing agents, manufacturers can tailor material characteristics to meet specific packaging requirements, such as improved mechanical strength, barrier properties, and biodegradability.

Blending involves combining two or more polymers to create a material that exhibits the advantageous properties of each constituent. For instance, PLA plasticization can be carried out to improve the overall crystallinity by blending it with other polymers such as starch, citrate ester, and sorbitol. Such blending of PLA usually occurs under shear force using an extruder. Blending PLA with copolymers is a commercially used method to improve its chemical compatibility with natural fibers and fillers. Studies have shown that when polymers such as PBS, PLA, and polycaprolactone (PCL) blend with grass fibers, it can result in increased tensile strength and modulus. However, it led to a reduction in overall impact strength. This enhancement is attributed to the formation of cross-linked structures from the copolymer blend, which effectively entangles the fibers and promotes stronger bonding with the PLA matrix. Another study demonstrated that blending PLA with sugar palm starch improved its flexibility and reduced its brittleness, making it more suitable for packaging applications ([Ranakoti et al., 2022](#); [Sanyang et al., 2016](#)).

3.5.3 Additives for Improved Performance in Food Packaging

Various additives are often used to improve the properties of polymers that are used for food packaging applications. These additives can significantly improve mechanical strength, barrier properties, and functional attributes, making the materials more suitable for preserving food quality and extending shelf life.

Plasticizers are often incorporated by blending into aliphatic polyesters to enhance their flexibility and reduce brittleness. These additives work by increasing the mobility of polymer chains, resulting in improved ductility and reduced risk of breaking under mechanical stress. For example, glycerol and sorbitol are frequently used plasticizers in biopolymer films, effectively enhancing flexibility and resistance to fracture, which are critical for food packaging applications. Additionally, these plasticizers reduce the glass transition temperature (T_g) of the material, enabling better performance under low-temperature conditions typical of food storage environments ([Marasinghe et al., 2024](#)).

Another effective approach involves the incorporation of nanoclays into aliphatic polyester matrices. Nanoclays, such as montmorillonite, form plate-like structures that align within the polymer, creating a layered barrier that restricts the movement of gas and moisture molecules. However, the effectiveness of nanoclays heavily depends on factors such as the type of clay content, aspect ratio, and dispersion method. For example, PLA nanocomposites prepared with Cloisite 30B using melt blending and in situ polymerization demonstrated promising enhancements in water vapor resistance. Notably, in situ, polymerized nanostructures exhibited two orders of magnitude lower water vapor diffusivity compared to melt-processed composites and neat PLA films. Nanoclays like montmorillonite also enhance barrier properties by forming plate-like structures within the polymer matrix, creating a tortuous path that restricts the movement of gas and moisture molecules. Such barrier tortuosity contributes to extended shelf life and better food preservation ([Singha & Hedenqvist, 2020](#)).

Additionally, some nanofillers impart antimicrobial properties, which are beneficial for food safety. Silver nanoparticles, when incorporated into aliphatic polyesters, inhibit the growth of microorganisms on the surface of the packaging, offering active protection against spoilage and contamination. There are various types of nanofillers used in aliphatic polymers as specified in [Table 3.3](#) ([Thakur et al., 2023](#)).

TABLE 3.3 Summary of Nanofillers Used in Aliphatic Polyesters and Their Role in Improving Food Packaging Performance ([Thakur et al., 2023](#)) ↵

<i>NANOFILLER TYPE</i>	<i>KEY PROPERTIES</i>	<i>RESULTS</i>	<i>REFERENCES</i>
Nanoclays	Plate-like structures; high surface area	Reduces oxygen permeability; improves thermal, mechanical, and gas barrier properties	(Bumbudsanpharoke & Ko, 2019)
Cellulose Nanocrystals	Renewable; high tensile strength	Enhances mechanical properties; biodegradable, UV-blocking, and antimicrobial properties	(Alkassfarity et al., 2024)
Graphene Oxide	High thermal stability; excellent mechanical reinforcement	Provides durability; reduces moisture permeability, mechanical, barrier properties, and antimicrobial activity	(Barra et al., 2020)
Zinc Oxide Nanoparticles	Antimicrobial activity	Prevents microbial growth; extends food shelf life	(Smaoui et al., 2023)
Silver Nanoparticles	Broad-spectrum antimicrobial properties	Protects food from bacterial contamination; possesses water vapor and oxygen barrier properties	(Cheng et al., 2021)

Antimicrobial agents play a vital role in extending the shelf life and ensuring the safety of food products when incorporated into aliphatic polyester-based packaging. Recent advancements have focused on integrating natural antimicrobial compounds, such as plant extracts, essential oils, and enzymes, into aliphatic polyester films to create active packaging systems. These systems not only protect food but also align with consumer demand for eco-friendly and sustainable packaging solutions. For example, chitosan, a biopolymer with inherent antimicrobial properties, has been widely used to enhance the effectiveness of biodegradable packaging films. When combined with essential oils such as thyme or natural extracts such as green tea, these films demonstrate significant antimicrobial activity against common foodborne

pathogens. Continuous advancements in nanotechnology have enabled the incorporation of nanoparticles like silver or zinc oxide into packaging materials, further enhancing their ability to inhibit microbial growth while maintaining mechanical and barrier properties ([Thakur et al., 2023](#)).

3.6 APPLICATIONS IN FOOD PACKAGING

3.6.1 Case Studies and Practical Applications

Aliphatic polyesters, particularly bio-based and biodegradable types such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and polybutylene succinate (PBS), have shown promising potential in food packaging. Here, we explore their practical applications and highlight specific case studies that underscore their effectiveness in enhancing food safety, shelf life, and sustainability. PLA is one of the most widely used aliphatic polyesters in food packaging due to its transparency, mechanical strength, and biodegradability. Its applications range from plastic films and trays to disposable cups and cutlery. This chapter will focus on a study by Moldovan et al., which focuses on enhancing the properties of PLA by integrating natural additives to create bioactive packaging materials aimed at extending the shelf life of packaged foods. In their study, six composite materials were formulated using PLA and a plasticizer, Proviplast 2624. The composites were infused with varying concentrations of grape pomace (0.5%, 1%, and 1.5%) and copper particles synthesized from PEG 600 and CuSO₄ (2%, 5%, and 8%). The incorporation of grape pomace and copper particles into PLA not only enhanced the material's flexibility but also introduced bioactive properties beneficial for food packaging applications. Grape pomace, rich in polyphenols, offers antioxidant properties, while copper particles exhibit antimicrobial activity. These attributes can potentially extend the shelf life of food products by mitigating oxidation and inhibiting microbial growth. Moreover, utilizing agricultural waste like grape pomace aligns with sustainability goals, promoting a circular economy approach in packaging material development ([Moldovan et al., 2024](#)).

On the other hand, PHAs are a class of biodegradable polymers produced by microbial fermentation, offering a sustainable alternative to conventional plastics in food packaging applications. A notable study by Bugnicourt et al. explored the use of PHA-based materials for packaging cheese, a food product that requires specific

packaging conditions to maintain its quality and extend shelf life. Cheese packaging must provide adequate barrier properties against moisture and oxygen to prevent spoilage and maintain flavor. The study demonstrated that PHA films possess suitable mechanical properties and can be processed into flexible films appropriate for wrapping cheese. Moreover, the inherent biodegradability of PHAs offers an environmentally friendly disposal option compared to traditional petroleum-based plastics. The researchers highlighted that PHA packaging materials could be composted after use, reducing the environmental impact associated with plastic waste.

However, the study also identified challenges in the widespread adoption of PHA-based packaging, including higher production costs and the need for further optimization of barrier properties to match those of existing synthetic materials. Despite these challenges, the case study underscores the potential of PHAs as a viable material for food packaging applications, particularly for products like cheese that benefit from the specific properties of PHA films ([“\(PDF\) Polyhydroxyalkanoate \(PHA\)” 2024](#)).

PNS, over the years, has also gained attention in the food packaging industry due to its favorable properties and environmental benefits. A European Union-funded project, SUCCIPACK (Development of active, intelligent, and sustainable food packaging using Polybutylene Succinate), highlights sustainable alternatives to conventional food packaging by bringing together 18 European companies aiming to develop innovative food contact materials based on PBS. The main goal of the project was to develop a technical solution to replace fossil fuel-based packaging with biodegradable and recyclable PBS packaging. This innovation promises a longer shelf life and better protection for foods. The SUCCIPACK project demonstrated several practical applications of PBS in food packaging: PBS was successfully utilized to produce films, trays, and pouches suitable for various food products, packaging producers could manufacture PBS-based materials using existing technologies, requiring only limited investments to transition from traditional plastics and finally the adoption of PBS packaging aligns with environmental goals by offering a biodegradable alternative to conventional plastics, thereby reducing plastic waste ([FCMs based on bio-based polybutylene succinate | Food Packaging Forum, 2015](#)).

3.6.2 Comparison with Traditional Packaging Materials

When comparing aliphatic polyesters to traditional packaging materials, several key factors come into play, including biodegradability, mechanical properties, barrier performance, and environmental impact. Understanding these differences is crucial for selecting appropriate materials for food packaging applications. PLA can decompose under composting conditions, reducing environmental pollution. In contrast, traditional plastics like polyethylene terephthalate (PET) and polyethylene (PE) are derived from petrochemicals and are not readily biodegradable, leading to long-term environmental persistence ([Hussain et al., 2024](#)). In terms of mechanical strength, traditional plastics often outperform aliphatic polyesters. For instance, PET exhibits higher tensile strength and flexibility compared to PLA, making it more suitable for applications requiring durability and resistance to mechanical stress. However, advancements in polymer blends and composites are enhancing the mechanical properties of aliphatic polyesters ([Adeyeye et al., 2019](#)). Effective barrier properties are essential in food packaging to protect against moisture and gases. Traditional materials like PET and PE provide excellent barriers to oxygen and water vapor, extending the shelf life of food products. Aliphatic polyesters generally have higher permeability to gases and moisture, which can be a limitation. Nonetheless, incorporating nanofillers and developing copolymers have shown improvements in the barrier performance of aliphatic polyesters ([Roohi et al., 2018](#)). The environmental footprint of packaging materials is also a significant consideration. Aliphatic polyesters, which are biodegradable and derived from renewable resources, offer a more sustainable alternative to traditional plastics. The production and disposal of conventional plastics contribute to greenhouse gas emissions and environmental pollution. Transitioning to biopolymers like aliphatic polyesters can mitigate these environmental concerns ([Grujić et al., 2017](#)). [Table 3.4](#) summarizes the comparison between aliphatic polyesters and traditional packaging materials.

3.6.3 Performance and Limitations in Real-World Applications

Aliphatic polyesters have gained significant attention in the food packaging industry due to their biodegradability and potential to reduce environmental impact. However, their performance in real-world applications presents certain challenges that need to be addressed. While aliphatic polyesters like PLA offer good mechanical strength and transparency, they tend to be more brittle compared to conventional plastics, which can limit their use in applications requiring high flexibility and durability. To address this, researchers have explored blending PLA with other polymers or incorporating plasticizers to enhance its toughness and flexibility.

Furthermore, effective food packaging materials must provide adequate barriers against moisture, oxygen, and other gases to preserve food quality. Aliphatic polyesters generally exhibit higher permeability to gases and water vapor than traditional petroleum-based plastics, which can compromise the shelf life of packaged foods. Efforts to improve barrier properties include the incorporation of nanofillers and the development of multilayer structures ([Perera et al., 2020](#)).

TABLE 3.4 Comparison of Aliphatic Polyesters and Traditional Packaging Materials in Key Performance and Environmental Aspects [↗](#)

<i>ASPECT</i>	<i>ALIPHATIC POLYESTERS</i>	<i>TRADITIONAL PACKAGING MATERIALS</i>
Biodegradability	Biodegradable under composting conditions, reducing environmental pollution	Non-biodegradable; persist in the environment for extended periods
Mechanical Properties	Tensile strength ranges from 37 to 60 MPa; ongoing improvements with polymer blends	Tensile strength ranges from 50 to 80 MPa; suitable for demanding applications
Barrier Properties	Higher permeability to gases and moisture; enhancements achieved with nanocomposites	Excellent barrier to oxygen and water vapor; effectively extends shelf life
Environmental Impact	Derived from renewable resources; lower carbon footprint and reduced pollution	Produced from petrochemicals; associated with higher greenhouse gas emissions

The relatively low glass transition temperature of some aliphatic polyesters, such as PLA, limits their application in packaging for hot-fill processes or microwaveable products. Therefore, enhancing thermal stability through copolymerization or the addition of heat-resistant additives is an area of ongoing research. Finally, cost considerations are important. The production costs of aliphatic polyesters are currently higher than those of conventional plastics, primarily due to the expenses associated with raw materials and manufacturing processes. This economic factor poses a barrier to their widespread adoption in the cost-sensitive food packaging market. Advancements in production technologies and economies of scale are expected to mitigate these cost issues over time ([Martins et al., 2022](#)).

3.7 ENVIRONMENTAL AND ECONOMIC ASPECTS

3.7.1 Life Cycle Assessments

A class of biodegradable plastics known as aliphatic polyesters, such as polyhydroxyalkanoates (PHAs), provides an environmentally sustainable alternative to conventional petroleum-based polymers. These materials break down naturally because they are composed of molecular chains linked by ester bonds, which are inherently susceptible to hydrolysis or microbial degradation. PHAs are produced by a large number of businesses worldwide. Within the United States, Metabolix Inc. and Meredian Inc. are among the key manufacturers. Biomer produces PHAs under the brand name Biomer® in Europe ([Montalbo-Lomboy, 2023](#)). In Brazil, PHB Industrial SA produces approximately 50 tons of polyhydroxybutyrate (PHB) and poly(hydroxybutyrate-co-hydroxyvalerate) (PHBV) annually using sugarcane as a raw material. Chinese companies such as Tianan Biologic Material Co. and Tianjin Green Bio-Science Co. have entered the market in recent years, with Tianjin Green Bio-Science producing up to 10,000 tons per year of poly(3-hydroxybutyrate-co-4-hydroxybutyrate).

PHAs are used in the development of eco-friendly products, including biodegradable packaging materials such as films, bottles, and containers ([Lawal & Valapa, 2021](#)). These polymers can break down naturally in diverse environments, including tropical climates and marine ecosystems, through microbial activity or hydrolysis. However, optimal degradation requires the right environmental conditions, sufficient moisture, favorable temperature, and microbial presence. Aliphatic polyesters are synthesized from naturally derived monomers such as lactide ($C_6H_8O_4$), glycolide, and ϵ -caprolactone. Their chemical structure is formed by repeating ester linkages, which helps them degrade naturally. Unlike conventional plastics that persist in the environment for centuries, aliphatic polyesters decompose through microbial activity and hydrolysis, reducing their ecological footprint ([Rosenboom et al., 2022](#)). However, they exhibit relatively lower mechanical strength and thermal resistance, which may limit their durability in certain applications.

Kijchavengkul studied the application of biodegradable films made from modified aliphatic polyester as mulch films in agriculture, specifically for tomato farming. These films were mixed into the soil after harvesting, in contrast to conventional polyethylene films that need to be removed and disposed of, which can be expensive.

According to the study, photodegradation was brought on by exposure to ultraviolet (UV) light, which eventually caused the films to break and become brittle. The pigmentation of the film affected the rate of degradation; white films containing titanium dioxide degraded in two weeks, while black films containing carbon black took about eight weeks to degrade. Compared to traditional plastic mulch, the use of biodegradable mulch films has a number of benefits, such as better soil moisture retention, less evaporation, and a smaller environmental impact due to the removal of plastic waste from landfills. The importance of biodegradable alternatives is further highlighted by the fact that conventional mulch films cannot be recycled because of contamination and degradation-related issues ([Kijchavengkul et al., 2008](#)).

Polymers are macromolecules composed of repeating monomeric units. Polymers such as polyethylene and nylon, which have been widely used, exhibit high durability but lack biodegradability, contributing to long-term environmental pollution. Consequently, researchers are exploring alternatives that decompose naturally under environmental conditions. Biodegradable polymers often consist of amino acid-derived monomers, forming polypeptides with favorable mechanical properties such as strength and flexibility. However, the production of synthetic polypeptides and poly(amino acids) remains economically challenging. In contrast, synthetic polymers such as nylons, which share some structural similarities with proteins, are more cost-effective yet are not readily biodegradable due to their robust amide linkages ([Kamaly et al., 2016](#)).

Given these limitations, ester-based polymers have emerged as promising candidates for biodegradable materials. Ester bonds are more susceptible to hydrolysis compared to amide linkages, facilitating faster degradation in aqueous environments. This property is particularly advantageous in natural settings such as soil, aquatic ecosystems, and even biological systems. While ester-based polymers may not exhibit the same degree of intermolecular interactions as proteins, they offer a viable balance between functional properties and environmental sustainability. Aliphatic polyesters, like polyhydroxyalkanoates (PHAs), are a type of biodegradable plastic that is environmentally friendly. These plastics are made up of chains of molecules that can break down when exposed to water or microbes (like bacteria). The chains are connected by ester bonds, which are vulnerable to breaking down over time, making these plastics biodegradable ([Mukherjee et al., 2023](#)). PHAs are used to create eco-friendly products like biodegradable packaging, including plastic foils, bottles, and containers. These materials are biodegradable, meaning they break down naturally in the environment. Studies have shown that PHAs can degrade in different environments, including tropical climates and even in the ocean ([Suzuki et al., 2021](#)).

The breakdown process involves the action of microorganisms or the simple chemical process of hydrolysis, where water breaks down the material. However, for this to happen efficiently, the presence of water and the right conditions for microbial activity are necessary. In summary, PHAs are a promising biodegradable alternative to traditional plastics, and their breakdown is influenced by environmental factors like water, temperature, and the presence of microorganisms.

3.7.2 Challenges in Widespread Adoption for Food Packaging

Despite the environmental benefits of biodegradable packaging materials, several challenges hinder their extensive application in the food packaging industry. A primary concern is their susceptibility to degradation through thermal, photo-induced, and chemical mechanisms. Key limitations include insufficient thermal and mechanical stability. Many biodegradable polymers exhibit poor heat resistance and limited mechanical strength, which can compromise the structural integrity of packaging materials. These deficiencies restrict their use in applications requiring durability and extended shelf life ([Marasinghe et al., 2024](#)). These polymers also exhibit suboptimal barrier properties. Biodegradable packaging materials often have inadequate moisture and gas barrier properties, which can lead to reduced food preservation effectiveness compared to conventional synthetic polymers. This limits their suitability for packaging perishable food products (V et al., 2022).

Processing of aliphatic polyesters is a huge challenge. Certain biopolymers demonstrate poor processability due to weak melt rheology and high sensitivity to heat. These properties present difficulties in traditional polymer processing techniques, making large-scale manufacturing complex and costly ([Cheng et al., 2024](#)). Another big issue is regulatory gaps and standardization. The commercialization of biodegradable food packaging is further constrained by the lack of clear legal guidelines and standardized regulations governing biopolymer applications. The absence of uniform biodegradation testing protocols results in inconsistencies in performance evaluation and market acceptance ([Cheng et al., 2024](#)). Environmental and storage sensitivity is another key challenge for the adoption of aliphatic polyesters for food packaging. The efficacy of biodegradable packaging varies significantly depending on storage conditions, such as humidity and temperature. These environmental factors can accelerate degradation, affecting the stability and functional performance of packaging materials.

To address these challenges, several strategies have been developed: material modification and polymer blending, chemical, physical, and enzymatic

modifications, optimization of manufacturing processes, and regulatory development and standardization. The incorporation of reinforcing agents, copolymerization, and polymer-blending techniques can enhance the mechanical strength and barrier properties of biodegradable materials, making them more viable for food packaging applications ([Krithika, 2019](#)). Tailoring the chemical and physical properties of biopolymers through advanced modification techniques improves their performance, enabling them to meet industry requirements ([Suri & Singh, 2023](#)). Enhancing production efficiency and utilizing cost-effective, widely available biopolymers can contribute to reducing manufacturing costs while maintaining product functionality. Establishing standardized biodegradation testing methods and implementing new policies can promote the reliable and consistent evaluation of biodegradable packaging solutions, facilitating broader industry adoption. By addressing these technical and regulatory challenges, biodegradable food packaging can become a more competitive and sustainable alternative to conventional plastic packaging, supporting global efforts toward reducing plastic waste and environmental impact ([Marasinghe et al., 2024](#)).

3.8 FUTURE OUTLOOK

3.8.1 Advanced Development in Aliphatic Polyesters

Aliphatic polyesters have gained significant attention in recent years due to their biodegradability, biocompatibility, and versatility, making them ideal candidates for various industrial and biomedical applications. Their environmentally friendly nature, derived from renewable resources, positions them as promising alternatives to traditional fossil-based polymers, reducing carbon emissions and environmental pollution. Despite their numerous advantages, the inherent properties of aliphatic polyesters often require modification to enhance their mechanical strength, thermal stability, and functional performance for specific applications. Recent advancements have focused on tuning these characteristics through innovative processing techniques, composite formulations, and novel synthesis approaches ([Tang et al., 2025](#)).

One of the most significant advancements in the processing of aliphatic polyesters lies in the adoption of 3D printing technologies, which offer exceptional precision and customization for complex structures. Among the commercially available

techniques, selective laser sintering (SLS) and fused deposition modeling (FDM) have been extensively employed for shaping aliphatic polyester-based materials. In the SLS technique, a high-powered infrared laser selectively fuses polymeric powders, including thermoplastic polyurethanes (TPU) and polyamides, layer by layer, resulting in highly detailed and mechanically robust structures ([Kafle et al., 2021](#)). Though commonly used for metals and ceramics, SLS's application to aliphatic polyesters is emerging due to its capacity to produce complex geometries with controlled physical and mechanical properties. FDM, on the other hand, involves the extrusion of thermoplastic polymer filaments, which are deposited in successive layers to construct a 3D object. The physical adhesion between layers ensures structural integrity as each layer cools and solidifies. This technique is particularly advantageous for aliphatic polyesters due to its cost-effectiveness, ease of use, and capacity to fabricate customizable architectures ([Chiulan et al., 2018](#)).

The rising demand for sustainable and environmentally friendly materials has driven the development of green composites based on aliphatic and aromatic polyesters. These biopolymers, often derived from naturally occurring and renewable resources, offer biodegradable and non-toxic properties, making them suitable for various industrial applications. By incorporating fillers and nanomaterials, the mechanical, thermal, and functional characteristics of these polyesters can be tailored to meet the demands of diverse sectors, including food and beverage packaging, textiles, biomedical devices, and high-performance engineering applications ([Ghosh et al., 2019](#)).

Aliphatic polyesters have long been used in drug delivery applications due to their biocompatibility and controlled degradation profiles. Their ability to undergo ring-opening polymerization enables the synthesis of amphiphilic block copolymers, which can self-assemble into nanoparticles, micelles, and polymersomes. These drug carriers offer tunable degradation rates, mechanical properties, and functional performance, allowing for the precise release of pharmaceutical compounds. The integration of targeting moieties and stimuli-responsive groups further enhances their efficacy, enabling site-specific drug delivery and minimizing systemic side effects ([Washington et al., 2017](#)).

In the field of regenerative medicine, aliphatic polyester-based nanocomposites have matrices and nanofillers ([Armentano et al., 2018](#)). Advanced copolymerization strategies, combined with nanoparticles of varying shape, size, and content, have led to materials with improved thermal stability, electrical conductivity, and controlled biodegradation rates. These nanocomposites exhibit enhanced cell adhesion, proliferation, and differentiation, making them suitable for the development of

scaffolds, artificial tissues, and other biomedical devices. The ability to fine-tune surface characteristics and mechanical properties through nanofiller incorporation has opened new avenues for the design of bioactive and functionalized materials for tissue engineering applications ([Armentano et al., 2018](#)).

The advancements in aliphatic polyesters have significantly broadened their application scope, driven by innovations in processing technologies, sustainable material development, and functional performance enhancements. The integration of 3D printing, green composite formulations, and nanotechnology has enabled the creation of highly customizable, efficient, and eco-friendly materials suitable for various industrial and biomedical fields. As research continues to explore novel synthesis methods and material modifications, aliphatic polyesters will likely play an increasingly prominent role in shaping the future of sustainable and advanced material solutions ([Armentano et al., 2018](#)).

3.8.2 Potential for Improving Sustainability in Packaging

Aliphatic polyesters hold significant potential for improving sustainability in packaging due to their renewable origin, tunable properties, and environmental benefits. Derived from bioderived monomers like lactones, menthide (a derivative of plant-based menthol), and lactide (LA), these polyesters offer a viable alternative to petroleum-based plastics. Their ability to degrade safely and efficiently under controlled conditions addresses major end-of-life disposal issues, making them attractive for eco-friendly packaging. Beyond their sustainability, aliphatic polyesters can be engineered to exhibit impressive mechanical strength, flexibility, and thermal stability, comparable to commercial styrene block copolymers. For instance, fully renewable PLA–PM–PLA triblock copolymers have demonstrated microphase separation and high-performance properties, making them suitable for durable packaging applications. Innovations in material design, such as the development of triblock copolymers with α -methylene- γ -butyrolactone (MBL) and 6-methyl caprolactone (MCL), further expand the versatility of aliphatic polyesters, offering enhanced mechanical properties even at elevated temperatures. These advancements enable the production of packaging materials with tailored performance characteristics like impact resistance, elasticity, and adhesive strength while maintaining environmental responsibility. As the demand for sustainable alternatives grows, the development of fully renewable and degradable aliphatic polyester-based materials presents a promising solution for the future of sustainable packaging ([Hillmyer & Tolman, 2014](#)).

Aliphatic polyesters, including PLA, PHA, PBS, and PCL, have gained significant attention as sustainable alternatives to conventional fossil-based plastics. Their biodegradability, bio-based origins, and mechanical properties make them promising candidates for various packaging applications. However, their sustainability depends on multiple factors, including sourcing, production processes, end-of-life disposal, and overall environmental impact. One of the key advantages of PLA and PBS is their potential for carbon neutrality or even carbon negativity due to the uptake of CO₂ during plant-based feedstock cultivation. For instance, PLA production using renewable energy sources significantly reduces its carbon footprint, making it a more sustainable option compared to conventional plastics. However, while PLA is biodegradable under industrial composting conditions, it has a relatively slow degradation rate in natural environments. This limits its effectiveness in uncontrolled disposal scenarios, raising concerns about its role in circular economy models. Similarly, PHA, which is produced through microbial fermentation, is considered one of the most sustainable aliphatic polyesters due to its ability to biodegrade in various environments, including marine and soil ecosystems ([Swetha et al., 2023](#)). This makes it an ideal material for single-use packaging, particularly in applications where recycling is not feasible. However, its high production cost remains a barrier to widespread adoption.

The end-of-life scenario plays a crucial role in determining the environmental benefits of aliphatic polyesters. While industrial composting can efficiently degrade these materials, current waste management infrastructure in many regions is not equipped to handle biodegradable plastics separately. Mechanical recycling of aliphatic polyesters, particularly PLA, is possible but not widely implemented due to low collection volumes and contamination risks. Incineration and landfilling, though commonly used, reduce the sustainability benefits by contributing to CO₂ emissions and resource depletion. Another critical aspect is the competition with food crops for raw materials. Since most aliphatic polyesters are derived from agricultural feedstocks like corn, sugarcane, and soy, concerns exist regarding land use and resource allocation. To further enhance the sustainability of aliphatic polyesters in packaging, ongoing research is being done to improve their mechanical performance, barrier properties, and biodegradation rates. In conclusion, aliphatic polyesters offer a viable route toward sustainable packaging, but their potential can only be fully realized with advancements in material performance, waste management, and production efficiency. A holistic approach considering both environmental and economic factors will be necessary to integrate them effectively into a circular economy model ([Reichert et al., 2020](#)).

3.9 CONCLUSION

Aliphatic polyesters, which strike a balance between performance, environmental advantages, and biodegradability, are an essential step toward developing sustainable food packaging solutions. Although their structural adaptability and modification potential enable customized applications, issues with cost-effectiveness, large-scale manufacturing, and end-of-life management still exist. Further developments in waste management infrastructure and regulatory frameworks will be necessary for their successful market integration, even as advancements in polymer chemistry, functionalization, and recycling techniques continue to increase their usefulness. The long-term sustainability of aliphatic polyesters as a component of environmentally friendly packaging will be decided by interdisciplinary efforts in material science, policy formation, and industry cooperation.

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Protein-Based Biomaterials in Food Packaging 4

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4.1 INTRODUCTION

Protein-based biopolymers (PBBs) are a dynamic and diverse class of natural or synthetic materials that have recently garnered significant interest in food packaging ([Abascal & Regan, 2018](#)). The increase in food demand and dependence on processed food boomed after the Industrial Revolution. The food packaging industry is dealing with food shelf life and sustaining its availability for a longer duration. An ideal packaging material is mass-produced, cost-effective, and preserves the freshness, quality, and safety of the food material while making it convenient to transport and store. Initially, synthetic materials, especially plastic, were used in the packaging industry. Environmental and health concerns associated with non-degradable synthetic materials shifted the research paradigm toward the development of sustainable, biodegradable, and compatible biopolymers for food packaging. The food industry dived into the development of biodegradable and edible films to satisfy the need for shelf-stable processed

food ([Kabir et al., 2020](#)). Protein has been an intrinsic part of the food industry for ages for its usage as a dietary component, but its usage as a packing material in the food industry is novel. Proteins are an attractive option in the food packaging industry due to their biocompatibility and biodegradability, ultimately being reintegrated into the earth's biomass ([Leya et al., 2024](#)). Moreover, proteins are highly customizable and processable, which is important for generating films or bio-coating of specific interest. These features are attributed to the structural diversity inherent in protein molecules. The diversity in protein polymers is due to the variable arrangement of 20 different amino acids, which fold into secondary and tertiary functional structures. These structural arrangements ensure the unique physicochemical properties that can be extensively exploited in the food packaging industry.

Naturally, proteins are present as the structural (collagen, keratin) or functional (enzymes) units in living systems. PBBs hold potential for the food industry as they are transparent, gas-resistant, and have high tensile strength ([Zhen et al., 2022](#)). The applicability of PBB in the food industry varies depending on the source of protein, the natural properties of a particular protein, and its availability in nature. Usually, animal or plant-based storage proteins, including milk protein and endosperm storage proteins, are used for biopolymer formation ([Guo et al., 2022](#)). Over time, traditional extraction procedures have been refined to increase the yield and purity of selective proteins from the natural source without affecting their properties. However, extracted proteins can't be used as such in the process of forming films due to certain physicochemical properties, including low water vapor resistance and temperature sensitivity ([Bhaskar et al., 2023](#)). However, these shortcomings can be addressed by altering the natural properties of protein and by adding certain agents (crosslinking chemical agents, plasticizers, antioxidants, and antibacterial agents) with desired properties. Therefore, after extraction, natural proteins undergo several rounds of chemical and physical modifications to enhance their functionality as packaging material ([Fahmy et al., 2020](#)). Various strategies, such as crosslinking with additional protein molecules, the addition of

plasticizers, incorporation of natural antioxidants or antimicrobial agents, surface modifications, and the addition of functional groups, have been developed to modify natural proteins before turning them into films/bio-coatings ([Shams et al., 2019](#); [Wu et al., 2019](#)). Although it is not practical to rely on the natural system to extract proteins of interest, recombinant synthesis techniques facilitate the design of proteins of interest and their high-scale production in controlled systems by using genetically modified microorganisms as expression systems. In the current chapter, we will be discussing the advancements in packaging material, a shift of the food industry toward PBB as films/bio-coatings, and the properties of PBB that make them attractive options to be used in the food industry. Various animal- and plant-based proteins that have been actively used in the food industry will be elaborated along with their properties, extraction procedures, scope of modification, and their present status in the food industry. The detailed insight into the benefits of using PBB and the needs of the future food packaging industry concerning PBB will be essential for future research programs.

4.2 ADVANCEMENTS IN PACKAGING MATERIALS

Over the past 70 years, researchers have explored various types of foils and layers designed to prevent food spoilage. Packaging materials have been enhanced enormously with advancements in the food industry. Various packaging materials are used, including glass bottles, metal cans, paper boxes, and jars for liquids and pickled products. Metal cans are common for vegetables, fruits, and soups, while plastic containers, bags, and bottles suit liquids, powders, and solids. Paperboard boxes and cartons are used for dry goods. Nanotechnology has enabled nanocomposite laminates to be used to package baked goods. Flexible packaging, like plastic laminates, foils, and films, is often utilized for vacuum and pouch packs ([Bhaskar et al., 2023](#)).

However, the use of conventional plastics in the packaging industry raises economic and environmental concerns ([Hurley et al., 2013](#)). This problem drove the food packing firms toward the development of economic and safe biomaterials, with PBB being a potential candidate that is highly versatile, biocompatible, and biodegradable ([Jabeen et al., 2015](#); [Bhaskar et al., 2023](#)). Historical records from Japan indicate that edible films were made from protein extracted from soymilk in the early 15th century. The progress of PBB and coatings has advanced significantly over the years. Research into using proteins for food packaging began in the 1960s, driven by the search for biodegradable alternatives to traditional plastics. The first protein used as an edible film was casein, derived from milk, in the 1970s. It showed promising barrier and mechanical properties, making it suitable for packaging dairy harvests like butter and cheese ([Meshram et al., 2022](#); [Khwaldia et al., 2010](#)). Followed by it's in the 1980s, soy protein isolates gained popularity as films due to their high strength and flexibility, which was beneficial for increasing the shelf life of fruits, vegetables, and animal-based food commodities. In the 1990s, research was driven toward using collagen as an active protein for biofilm formation to preserve meat and seafood for a long period by exploiting the gas barrier properties of collagen. Protein-based edible films and coatings are now widely used in the food industry to package a variety of products, including snacks, baked goods, fresh produce, and confectionery; these films and coatings serve as edible barriers that regulate oxygen, flavor, and moisture transference in food. PBBs offer the opportunity to minimize the wastage of food and shield products from various factors such as microbes, toxins, hydration, gases, and harmful elements in the outside environment. However, there is a need for stringent trials to produce and use the edible biofilm while ensuring the safety of consumption and preserving the products for a longer period of time ([Shlush & Davidovich-Pinhas, 2022](#)). As a result, there has been a significant rise in interest in protein-based coatings and films in current ages, owing to their benefits compared to traditional petroleum-based materials and additional biological substances like lipids and polysaccharides. It is reported that the structure of a protein is vital for film

formation, as it influences the capacity of protein to network with itself and other commodities ([Zink et al., 2016](#)). These proteins can be readily treated and formed into films sourced from renewable materials, making them an additional sustainable substitute for conventional synthetic plastics.

Current studies are focused on expanding the range of utilizations of coatings and films formed from PBB through the exploration of innovative manufacturing and processing methods. Recent developments in food packaging have concentrated on improving the sustainability, safety, and cost-effectiveness of protein-based materials while enhancing their properties and expanding their uses ([Assad et al., 2020](#)). Along with it, other protein sources, including corn zein, wheat gluten, and rice bran proteins, were also explored as a source for biofilm formation, offering sustainable and cost-effective options for edible films ([Assad et al., 2020](#); [Zhen et al., 2022](#)). Overall, an innovative strategy is essential for developing various natural PBBs and their effective applications in various fields, especially for the food packaging industry.

4.3 EXTRACTION AND SYNTHESIS OF PROTEIN-BASED BIOPOLYMER (PBB) FILMS/COATINGS

The extraction and synthesis of coatings using PBB is a dynamic and versatile process. Multiple processes are involved in the extraction of desired proteins, followed by their processing to form films/coatings, in addition to certain modifications to enhance their properties for application in the food packaging industry ([Figure 4.1](#)).

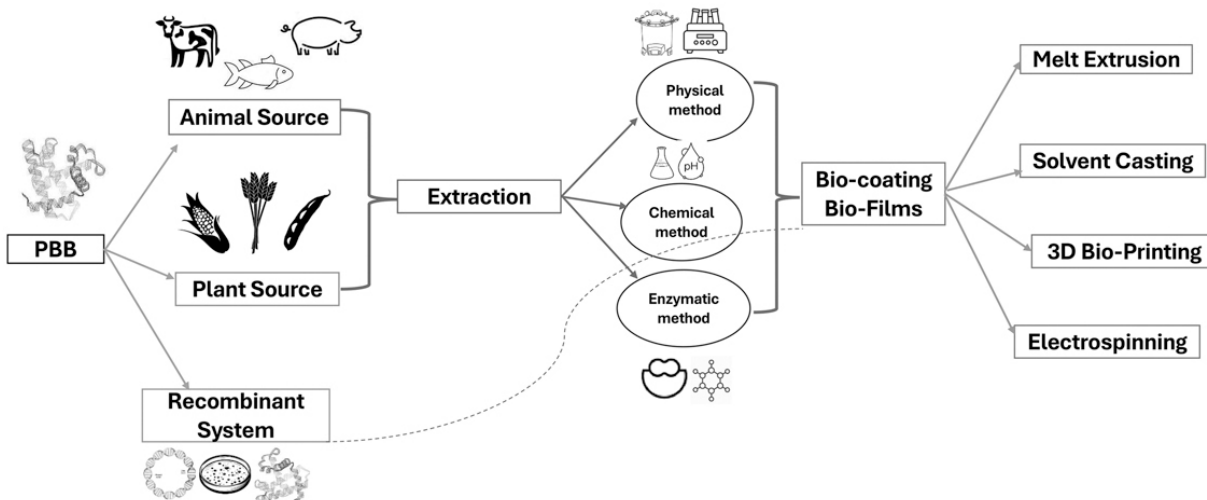


FIGURE 4.1 Elaborative procedure for formation of biofilm formation. [↗](#)

4.3.1 Extraction of Proteins from Natural Sources

Various chemical, physical, enzymatic, and radiation extraction methods have been used in isolation or in different combinations to fetch the protein of interest from its natural source. The choice of extraction method depends upon the intrinsic properties of the protein, its location in the natural system, and its interaction with other biopolymers present in a natural system. Among chemical methods, reactive solutions such as acid solid extraction and alkali solution-based extraction are used for collagen extraction ([Sousa et al., 2020](#); [Ahmed et al., 2020](#); [Gökalp et al., 2020](#)). Similarly, extreme change in pH followed by alkali treatment, and the starcher method is used for elastin extraction ([Daamen et al., 2001](#)). Starcher methods combine the physical method (autoclave), chemical method (chaotropic agents), and enzymatic treatments to ensure elastin extraction ([Soskel & Sandburg, 1983](#)). Certain extraction methods are designed by carefully observing the chemical properties of desired proteins; for example, zein is a hydrophobic protein that is extracted using ethanol ([Chen et al., 2013](#)). Among physical methods, steam explosion, autoclaving, sonication, and microwave are used to extract rigid proteins such as keratin ([Zhao et al., 2012](#)). Several physical extraction methods, including membrane filtration ([Chen et al., 2019a](#)), electro-membrane dialysis

([Greiter et al., 2004](#)), and resin-based chromatography ([Chen et al., 2023](#)), are used for whey protein extraction.

To enhance extraction efficiency, physical and chemical methods are combined; for example, hot alkali extraction has been the most promising technique for yielding purified elastin from the source tissue ([Mecham, 2008](#)). Similarly, various combinations of thermal and chemical treatments are applied for effective degumming with retention of silk fiber properties ([Luong et al., 2015](#)). Enzyme-assisted extraction, particularly with proteases, has been shown to improve protein recovery from soy flour ([Rosenthal et al., 2001](#)). Chemical and enzymatic hydrolysis are used for the extraction of structural proteins such as keratin ([Feroz et al., 2020](#)).

Along with physical and chemical methods, natural catalysts, which involve enzymes and microbes, are promising options for extracting protein of interest without altering its properties. Proteases are established as promising agents for protein extraction. With advancements in techniques for protein extraction, cavitation-assisted extraction is another widely studied phenomenon in the food industry ([Knorr et al., 2004](#)) and is known to enhance mass and heat transfer as well as facilitate cell disruption. Overall, multiple methods can be used in isolation or in collaboration to obtain a high quantity of purified proteins.

4.3.2 Synthesis of PBB in Recombinant Systems

Recombinant protein-based biomaterials are bioengineered materials developed through the integration of molecular biology and polymer science techniques ([Li et al., 2024](#)). These materials can be produced using various expression systems, such as *E. coli*, yeast, insect, and mammalian cells ([Kaur et al., 2018](#); [Tripathi & Shrivastava, 2019](#)). Among these, *E. coli* is commonly used for its advantages, including rapid proliferation, simple nutritional requirements, high expression levels, and scalability ([Karbalaei et al., 2020b](#)).

4.3.3 Development of Films/Coatings Using PBB

Biopolymers are extensively used and can serve as coatings or films. Biopolymer films are formed separately and later applied to food commodities, whereas bio-coatings directly form layers on the food products ([Dhumal & Sarkar, 2018](#)). Biopolymer-based materials must meet essential requirements such as mechanical strength, safety from the external environment, resistance to chemicals, and durability. PBBs possess excellent film-forming abilities, offering enhanced nutritional worth and eco-friendly films. In the 2000s, attention shifted to improving processing methods for protein-based coatings and films, including techniques such as extrusion, solvent casting, and the use of edible plasticizers to improve film quality, consistency, and production efficacy. Recent advancements have focused on enhancing the utility of these coatings and films by adding compounds with antimicrobial activities. Along with it, antioxidants and bioactive components can be introduced to improve and enhance the shelf life of packed food while retaining its natural properties. This has led to a growing interest in intelligent packaging solutions with additional features ([Purewal et al., 2023](#)). Different techniques have been used to form PBB films, including the dry method and the wet method. The dry method comprises compression, molding, and extrusion of biopolymers, whereas the wet method comprises solvent casting. In both processes, proteins are denatured using either the physical method (heat) or the chemical method, that is, acid-base treatment or solvent addition. The more the extension, the greater the interaction and association among protein chains. Protein films are usually hydrophilic, which makes them resistant to water vapors in comparison to synthetic polymers used by packing industries ([Bhaskar et al., 2023](#)).

One of the most popular methods used commercially for food packaging is melt extrusion. In this process, the polymer blend is melted and extruded through a rotary extruder. Its high degree of customizability and straightforward production procedure make it an attractive option for commercial applications. However, melting of the polymers demands significantly higher temperature and energy, which degrades intrinsic protein structure and limits its use for producing biopolymeric films ([Calva-](#)

[Estrada et al., 2019](#); [Chen et al., 2019b](#); [Mohammed et al., 2020](#)). The solvent casting came out as an alternative method to surpass the limitations associated with the melt extrusion method. In this process, a solution containing biopolymer is dispensed onto a flat surface, and a solvent is allowed to evaporate. This method is preferred due to its low energy demand in comparison to melt extrusion and is inexpensive and easy to implement, requiring only basic equipment such as plastic and glass plates ([Priyadarshi et al., 2022](#)). However, industrial application of the solvent casting method is restricted due to its long drying times and multiple manual steps, making it challenging to scale for industrial applications. In this context, 3D printing is faster and more scalable than industrial applications, with the ability to substitute both extrusion and solvent casting methods. Furthermore, 3D printing offers greater consistency in film characteristics because of mechanized control over the printing process ([Leontiou et al., 2023](#)). Despite its advantages over the laboratory-scale method of solvent casting, there is still limited research on the potential of 3D bioprinting.

Electrospinning is another method investigated for biofilm formation. In this method, high voltage is applied to a polymeric solution, and fibers are deposited onto a collector ([Aytac et al., 2020](#); [Wang et al., 2021](#)). Biofilm made using the electrospinning method has a high surface-to-volume ratio and contains bioactive compounds that help reduce oxidation in nuts and grains. However, the energy requirements for electrospinning are high ([Singh et al., 2020, 2023](#); [Shao et al., 2019](#)). Due to the increasing requirement for environmentally friendly packaging polymers, the production of PBB edible coatings and films continues to be a vibrant area of research. Efforts are focused on refining their mechanical characteristics, barrier capabilities, and overall performance to satisfy the changing demands of the various industries, particularly the food packaging industry.

4.4 PROPERTIES OF PROTEIN-BASED MATERIALS

The physicochemical characteristics of PBB coatings and films are closely linked to their plasticity, which includes factors like mechanical strength, moisture content, thickness, thermal properties, sensory characteristics, water vapor permeability, and adaptability to conservational conditions. Further modification strategies are incorporated to enhance their properties ([Bhaskar et al., 2023](#)) ([Figure 4.2](#)).

In packed products, the freshness and shelf life of the product can be enhanced by favorable biochemical changes occurring on the surface. Additionally, various other factors, such as antioxidants, flavors, probiotics, antimicrobials, and nanomaterials, are acknowledged to enhance food quality ([Brigham, 2017](#)). Effective packaging of food should also possess discernible gas barrier and permeability properties. Keeping in view that proteins have several advantages, including abundance, excellent film-forming capabilities, and high nutritional value, they are widely used for biodegradable film production. Additionally, the mechanical characteristics of PB films and their gas barrier properties surpass films made from other polymers, including polysaccharides and lipids ([Bourtoom, 2009](#); [Zhen et al., 2022](#)).

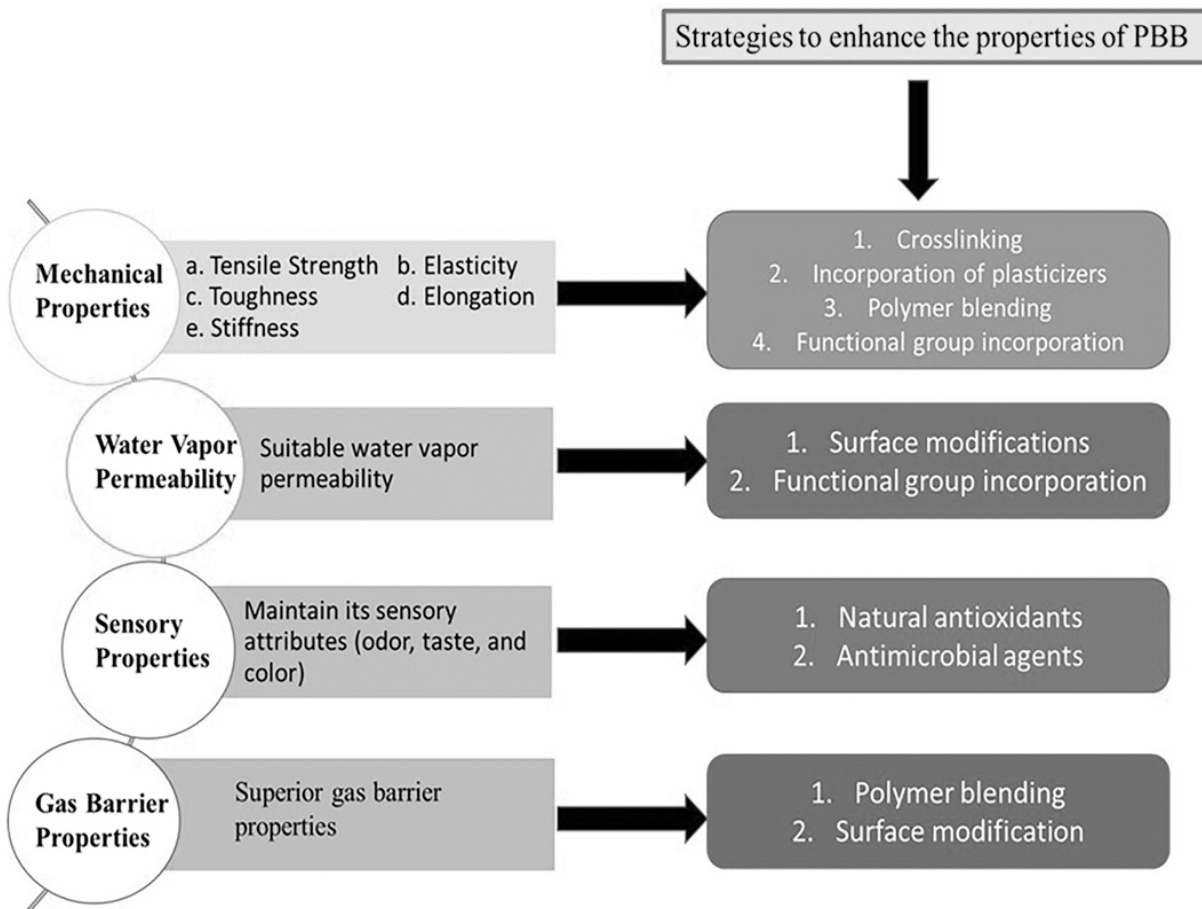


FIGURE 4.2 Outline of properties associated with protein for its usage as PBB. [↗](#)

4.4.1 Structural Properties

Protein polymers have diverse structural properties. These properties are associated with the dynamic arrangement of amino acids, which forms the primary structure of protein and its further folding into secondary, tertiary, and quaternary structural forms. PBB's high structural arrangements (secondary and tertiary structure) are due to several covalent and non-covalent interactions. A quaternary structure is formed when several protein subunits join together either through interprotein linkage or due to association with some functional group. Overall, the hierarchy of structure arrangement adds to complexity and enhances functional diversity in natural systems. Proteins in natural systems can be broadly classified as fibrous and globular proteins. Fibrous protein has repetitive amino acid

sequences that endow these proteins with high mechanical strength. The repetitive sequence leads to the formation of beta-sheets, triple helices, or curls, which enhance the self-polymerization of proteins. Fibrous proteins such as collagen, silk, and keratin form the structural components of natural systems ([Tunuh et al., 2025](#)). Globular proteins have a continuous amino acid sequence, which preferably forms alpha-helices as the secondary structure and folds into a compact spherical shape while forming a stable tertiary structure. Several functional and storage proteins come under the category of globular proteins, including enzymes, hemoglobin, zeins, and whey protein. The structural variability of PBB is essential to form stable films and coatings for food packaging ([Hassan et al., 2024](#)).

4.4.2 Mechanical Properties

The mechanical strength of PB films is essential in maintaining the integrity of edible materials throughout their lifespan ([Assad et al., 2020](#)). Protein-based films exhibit several key mechanical properties important for food packaging applications, such as tensile strength, elasticity, toughness, elongation, and stiffness. These properties help to measure the capacity for enduring negative factors, their ability to stretch and revert to their original shape, the energy required to break the films, flexibility, and resistance to bending ([Oymaci & Altinkaya, 2016](#); [Assad et al., 2020](#)). The mechanical properties of PB coatings/films are primarily affected by several factors, such as the type of protein used and the preparation and processing techniques used. For example, silk protein-based films have strengths ranging from 0.4 to 19 MPa, while whey protein-kefir composite films have strengths between 3.16 and 3.95 MPa, whey protein-based edible film (strength: 0.7–1.8 MPa, thickness: 129.9–153.3 μm), whey PBB edible coatings/films (strength: 0.7–1.8 MPa, thickness: 100–160 μm), soy protein isolates film (strength: 7.09–7.88 Mpa) are known for high mechanical properties ([Lyu et al., 2022](#); [Gagliarini et al., 2022](#); [Papadaki et al., 2022](#); [Chen et al., 2022](#); [Jiang et al., 2023](#); [Sun et al., 2023](#)), while other PB films such as packaging films based upon whey protein-cellulose nanocrystal,

whey PB films, soy protein isolate along with sodium alginate edible films, and soy protein isolate films, are particularly effective in providing strong barriers against oxygen and moisture ([Sun et al., 2023](#); [Papadaki et al., 2022](#); [Chen et al., 2022](#); [Jiang et al., 2023](#)). To effectively protect food and endure the pressures of processing, handling, and storage, protein-based biomaterials must possess excellent mechanical properties ([Olabarrieta, 2005](#); [Montes-de-Oca-Avalos et al., 2020](#); [Maroufi et al., 2021](#); [Herbes et al., 2022](#)). Improvements in these properties can be achieved through structural modifications and various strategies that influence the distribution and strength of molecular interactions (intra as well as intermolecular) within the chain of polymers ([Mihalca et al., 2021](#)). Additionally, the type and quantity of plasticizers and other additives, such as nanoparticles and antioxidants, can have a substantial impact on the mechanical characteristics of films and coatings ([Assad et al., 2020](#); [Fahmy et al., 2020](#); [Salgado et al., 2021](#)).

4.4.3 Water Vapor Permeability (WVP)

Water vapor permeability, also known as the water vapor transmission rate (WCTR), is a critical feature for the packaging of foods, as it directly impacts the shelf life of stored products ([Andrade et al., 2021](#)). WVTR measures the rate at which water vapor passes from the material, which is usually expressed in terms of grams per square meter per day ($\text{g/m}^2/\text{day}$) ([Schmid et al., 2012](#)). Biopolymers with low water vapor permeability help extend the freshness of packaged food by reducing moisture transfer, thus preventing discoloration, spoilage, and flavor loss. Moreover, low water vapor absorptivity contributes to maintaining the food's texture ([Mihalca et al., 2021](#)). Certain PBB, such as whey protein-cellulose nanocrystal packaging films ($2.82\text{--}3.18 \text{ gs-1m-1Pa-1}$), whey protein-based edible films ($6.2\text{--}12.8 \text{ gs-1m-1Pa-1}$), soy protein isolate/sodium alginate edible films ($3.55\text{--}5.15 \text{ gs-1m-1Pa-1}$), and soy protein isolate films ($0.86\text{--}1.19 \text{ gs-1m-1Pa-1}$), exhibit high water vapor permeability ([Papadaki et al., 2022](#); [Chen et al., 2022](#); [Jiang et al., 2023](#); [Sun et al., 2023](#)). The higher

water vapor permeability of these protein-based films makes them suitable for the packaging of food items.

4.4.4 Sensory Properties

Sensory assessment of PBB is essential for their marketplace success. Incorporation of compounds with bioactivity could critically impact physical perception ([Mihalca et al., 2021](#)). The sensory qualities of PBB should remain unaffected by the addition of bioactive composites ([Salgado et al., 2021](#); [Zemljí et al., 2023](#)). These sensory properties include how the packaging interacts with the food, influencing attributes such as odor, taste, and color that ultimately impact the general observation of food eminence ([Salgado et al., 2021](#)). Organoleptic properties are crucial for managing the formulation procedure, adjusting or deactivating active components in film constructions, and selecting suitable packaging designs, thus ensuring proper storage and handling. [Bugnicourt et al. \(2013\)](#) developed modified whey protein isolates by treating them with ethylene vinyl alcohol copolymers/polyamide, resulting in an improved oxygen blockage with transmission rate down to ranges of $1 \text{ cm}^3 \text{ (STP) m}^{-2} \text{ d}^{-1} \text{ bar}^{-1}$, having a reduced transmission rate while preserving both lifespan and sensory characteristics.

4.4.5 Gas Barrier Properties

Gas barrier properties refer to how gases, liquids, water vapor, and organic substances are transmitted through a material. The transmission process involves adsorption, dissolution, diffusion, and desorption. It is an important property of films and biopolymers to maintain the lifespan of food and other products. Protein-based polymers offer distinct advantages over polysaccharides and lipids, particularly due to their superior gas barrier characteristics. For instance, in soy protein-based films, the permeability of oxygen is 260, 500, 540, and 670 times less in comparison to the low-density methylcellulose, starch, polyethylene, and pectin, respectively ([Bourtoom, 2009](#)). Gelatin-based films are transparent, flexible, and exhibit

outstanding gas barrier characteristics ($5.02 \text{ cm}^3/\text{m}^2 \text{ day bar}$, 8-fold lower than polylactic films), making them appropriate for numerous applications, including the packaging of meat, fruits, vegetables, and confectionery items ([Luo et al., 2022](#)).

4.4.6 Thermal Properties

Thermal conductivity refers to the ability of a material to transport heat via a temperature gradient. Thermal conductivity is driven by charge carriers that transfer this energy from one system to another. In polymers such as PBB, heat transfer is mediated by lattice vibrations. Different PBBs have different thermal properties based on their structural orientations. Thermal properties of the protein further depend upon the structural properties of specific PBB, including molecular chain alignment, secondary structures, functional groups, interfaces, and chemical bonds ([Luckyanova et al., 2012](#); [Huang et al., 2012](#); [Xu et al., 2014](#)). Random molecular arrangements decrease the lattice vibrations, which decreases the overall thermal conductivity, whereas high molecular arrangements enhance the lattice vibration and increase the thermal conductivity ([Singh et al., 2014](#)). The thermal properties of PBB can be altered by changing the overall structural topology. In a study, the thermal conductivity of a hydrated tandem-repeat (TR) protein film was enhanced by changing its amorphous molecular conformations to a highly arranged network topology ([Tomko et al., 2018](#)). In the case of PBB, thermal conductivity is also dependent on the arrangement of the side chains. The thermal conductivity of PBB is not only influenced by the structural orientations, but it is also affected by external factors such as changes in temperature, moisture, and pH. Different PBBs have different thermal properties, which further change when bio-coating/films are made from such material. Various methods, including differential scanning and thermogravimetric approaches, are applicable to the analysis of thermal properties. Overall, an increase in the structural arrangement enhances the thermal properties. In the food packaging

industry, the thermal stability of PBB is preferred to enhance food storage and transport through changing thermal conditions ([Perera et al., 2023](#)).

4.5 STRATEGIES TO ENHANCE THE PACKAGING PROPERTIES OF PBB

Various modification techniques can be employed to enhance the physico-mechanical characteristics and reduce the water vapor permeability of these films. These include the following:

- a. **Crosslinking:** This process strengthens the film's mechanical properties by chemically bonding with adjacent protein fragments using agents like glutaraldehyde or CaCl_2 ([Purohit et al., 2019](#); [Mohammed et al., 2020](#); [Pushp et al., 2021](#)). Aldehydes, like formaldehyde and glutaraldehyde, are frequently used as crosslinking agents to boost the efficiency of the films. Formaldehyde is a common crosslinker that reacts with amino acids in a polypeptide, including cysteine, tryptophan, histidine, tyrosine, and arginine. However, glutaraldehyde is very selective, and it interacts with cyclic amino acids and positively charged lysine. Several studies show successful enhancement in properties of different PBB by adding crosslinking agents; for example, the addition of crosslinking agents such as glutaraldehyde and formaldehyde to gluten-based films enhanced water resistance by 30% ([Hernández-Muñoz et al., 2004](#)). [Jeon et al. \(2019\)](#) reported that crosslinking of cellulose nanofiber films with glutaraldehyde demonstrates approximately 180% tensile strength compared to the untreated film. Regarding the elastic modulus, the films show a value of 12.3 GPa, which is about 160% higher than that of the untreated film.
- b. **Incorporation of plasticizers:** Adding other polymers or plasticizers can enhance the flexibility and elongation of the protein films ([Purohit](#)

[et al., 2019](#); [Mohammed et al., 2020](#); [Pushp et al., 2021](#)). Soy protein-based films showed much lower oxygen permeability than methylcellulose, polyethylene, starch, and low-density pectin, although they had weaker mechanical properties ([Maurizzi et al., 2022](#); [Shit & Shah, 2014](#)). [Yu et al. \(2018\)](#) reported that the tensile strength of soy protein was improved by 40% with the incorporation of cellulose nanocrystals. To address these limitations, natural and/or biodegradable plasticizers were introduced to improve the films' viscoelasticity and extensibility. These plasticizers work by interacting physically and chemically with the polymer's molecular structure and bonds, enhancing its ductility, stiffness, elasticity, and overall mechanical properties. Factors including molecular weight, hydroxyl group arrangements, and quality define how a crosslinking agent will affect a PBB ([Purohit et al., 2020](#); [Singh et al., 2019](#); [Oymaci & Altinkaya, 2016](#)).

- c. **Natural antioxidants:** Active packaging has emerged as a significant focus of research in the food industry. Its innovative functionality arises from the interaction between the product, its environment, and the packaging. This approach improves the sensory qualities of the food while extending its shelf life. Antioxidants and antimicrobial agents are used in active packaging. It is referred to as active coating when it is incorporated into films. PBB films can serve multiple purposes, including the addition of nutritive value, enhancing texture, and adding antimicrobials and antioxidants ([Martucci et al., 2015](#)).

Compounds like vitamin E can be integrated to advance the stability and lifespan of the films ([Oymaci & Altinkaya, 2016](#); [Fahmy et al., 2020](#)). Oxidative processes are usually responsible for spoiling food products by reducing their natural color, flavor, and nutritional quality. These problems can be addressed by the addition of antioxidants to PBB ([Assad et al., 2020](#)). Preservation of food quality depends on the antioxidants used in functionalized food packaging. Plant extracts, including alpha-tocopherol, coumarin, ascorbic acid, and ferulic acid, act as the major source of natural antioxidants. Whey protein films are

associated with rosemary and thyme extracts that can be used as active food-packaging agents. Several properties of the protein films are based on the antioxidants added, including stronger antioxidant properties and better water resistance in soy protein isolates ([Guerrero et al., 2011](#)).

- d. **Anti-microbial agents:** Antimicrobial agents are added to the PBB films to prevent packed food from bacterial spoilage and to enhance its shelf life ([Zemljí et al., 2023](#); [Shlush & Davidovich-Pinhas, 2022](#)). Antimicrobial films and coatings can sustain high levels of active compounds on food surfaces. These compounds are released either through evaporation into the headspace if they are volatile substances or by diffusing into the food in the case of nonvolatile additives. A common approach to making these films is by adding natural antimicrobial agents to the protein matrix ([Zhen et al., 2022](#)). Essential oils from herbs and spices such as oregano, cinnamon, and cloves are recognized for their strong antibacterial properties ([Shams et al., 2019](#)). Plant extracts like thyme, rosemary, and grape seed also display antimicrobial effects ([Bhatia et al., 2022](#)). Natural substances like nisin, a peptide derived from *Lactococcus lactis*, can be incorporated into the packaging to shield food items from spoiling by bacteria and thus prolong their shelf life ([Shams et al., 2019](#)). These agents work by disrupting enzymatic processes, targeting phospholipid bilayers, and damaging bacterial genetic material. Nanoparticles, acting as nanofillers, serve as powerful antibacterial agents. They provide a broad-spectrum, stable, and low-volatility antibacterial effect ([Priyadarshi et al., 2022](#)). Silver and gold nanoparticles, in particular, are effective at low concentrations and help limit microbial growth in food ([Shams et al., 2019](#)). Furthermore, nano-silver and nano-gold can block ethylene production during fruit metabolism by facilitating its absorption and breakdown. For example, incorporating ZnO nanoparticles into packaging films can significantly extend their shelf life by adding antimicrobial fillers directly into the films or coatings ([Fahmy et al., 2020](#); [Salgado et al., 2021](#)). A controlled release system

ensures the antimicrobial agents maintain optimal concentrations to protect the food throughout its shelf life.

- e. **Polymer blending:** Combining protein films with other polymers like cellulose, chitosan, and alginate can enhance mechanical and barrier characteristics while also lowering expenses ([Wu et al., 2019](#)). A variety of proteins, such as keratin ([Bertini et al., 2013](#)), gluten ([Day et al., 2006](#)), milk protein ([Audic et al., 2003](#)), zein ([Khwalidia et al., 2010](#)), soy ([Tian et al., 2011](#)), silk ([Vepari & Kaplan, 2007](#)), and jatropha protein ([Lestari, 2012](#)), have been thoroughly studied, with results showing that composites made from these proteins offer significant potential for the advancement of natural polymers. Proteins like keratin and silk fibroin are more hydrophobic than cellulose-based agricultural fibers and have been used to form composites with synthetic polymers like polyethylene ([Hest & Tirrell, 2001](#); [Barone, 2005](#); [Bertini et al., 2013](#)). These composites are chemically compatible with the hydrophobic properties of polyethylene. According to [Barone and Schmidt \(2005\)](#), blending keratin with thermoplastics like polyethylene and polypropylene improves their glass transition temperature (T_g) and crystalline melting temperatures (T_m) ([Barone & Schmidt, 2005](#); [Barone, 2005](#)).
- f. **Surface modifications:** Applying different molecules like lipids or polysaccharides to the film's surface can enhance adhesion to other materials and barrier characteristics ([Wu et al., 2019](#)).
- g. **Functional group incorporation:** Inserting functional groups into the side chains of proteins permits both covalent and non-covalent cross-linking, enhancing film strength and hydrophobicity ([Wu et al., 2019](#)).

Additionally, tannins possess antibacterial properties, while cellulose nanocrystals (CNCs) help to reduce the percentage of water in protein-based films by disrupting hydrogen bonds among amine groups of protein and water molecules. This leads to stiffer films due to the CNC filling effect ([Bhatia et al., 2021](#)).

4.6 ANIMAL-BASED PROTEIN AS BIOPOLYMER

Animal-based proteins are a class of naturally occurring biopolymers composed of amino acids joined by peptide bonds. These macromolecules exhibit remarkable structural and functional properties, making them valuable for use in food, biomedical, and industrial fields ([Hooda et al., 2020](#); [Wang et al., 2022](#)). Animal-originated protein biopolymers are derived from various natural sources, including tissues, secretions, and structural components of animals. Their composition consists of amino acid sequences that determine their structural conformation and functional characteristics. Factors, including extraction methods and environmental conditions, influence their characteristics, leading to variations in their physical and chemical behavior ([Farhan & Hani, 2017](#)). Animal proteins that are used solely or in combination with other biopolymers to form films and coatings are discussed next.

4.6.1 Whey-Based Biopolymer

Whey is a distinct milk protein obtained as a by-product during cheese and yogurt production ([Abish et al., 2024](#)). Whey proteins (WPn) comprise 20% of total milk protein and are divided into five fractions: immunoglobulins (12%), bovine serum albumin (7%), β -lactalbumin (20%), β -lactoglobulin (52%), and peptones-proteoses (9%). WPn are proteins with globular structures that, when heated to pH 2, form fibrils that resemble amyloid ([Nagarajan et al., 2019](#)). Whey protein isolates (WPIs), which contain 90% protein, and whey protein concentrate (WPC), with a protein content ranging from 25% to 80%, are widely utilized for edible film production due to their superior barrier qualities against oxygen, aroma, and oil. They include amino acids containing sulfur, like cysteine and methionine, as well as essential amino acids like leucine, isoleucine, and valine ([Loveday et al., 2012](#)). The organoleptic properties of this milk protein are defined by its

appearance, color, smell, and taste ([Larionov et al., 2020](#); [Abish et al., 2024](#)). Whey proteins have gained popularity in film production due to their edibility, biodegradability, and ability to upcycle cheese-making byproducts. They also possess excellent mechanical properties, solubility, foaming, emulsifying, gelling, flexibility, and water-binding abilities ([Ramos et al., 2013](#)). It is often used as a coating material in paper packaging to improve gas barrier performance, providing advantages over traditional sizing agents and pigments ([Kumar et al., 2018](#)). Whey proteins stand out among film-forming biopolymers due to their ability to undergo conformational denaturation, their electrostatic charge, and their amphiphilic character ([Kaur et al., 2020](#); [Tavares et al., 2021](#)). The key processes for whey preconcentration in WPI and WPC production include ultrafiltration (UF), diafiltration (DF), reverse osmosis (RO), nanofiltration (NF), microfiltration (MF), and electrodialysis (ED) ([Chen et al., 2023](#)).

Whey protein films are usually created by casting a whey protein solution in ethanol or water and then allowing the solvent to evaporate and the protein to cross-link. As an alternative, the protein can be melted and formed into a film using extrusion techniques ([Rosseto et al., 2023](#); [Singh et al., 2021](#)). Numerous physical and chemical processes, such as UV irradiation, ultrasonic processing, alkalization, and the inclusion of plasticizers, can further improve the quality of whey-based films ([Oymaci & Altinkaya, 2016](#); [Lara et al., 2019](#); [Kandasamy et al., 2021](#); [Andrade et al., 2021](#)).

Additionally, whey-based films have antibacterial qualities and are efficient against *Aspergillus niger* (103 spores/ml). Films incorporating essential oils offer excellent barrier properties, improved water permeability, and enhanced flexibility ([Oymaci & Altinkaya, 2016](#); [Andrade et al., 2021](#)). Furthermore, the addition of montmorillonite (MMT) to WPI-based films greatly improves their mechanical and oxygen barrier qualities ([Schmid et al., 2017](#)). These films are ideal for packaging foods that are sensitive to moisture because of their exceptional water vapor permeability, high tensile strength, and flexibility ([Rosseto et al., 2023](#); [Cinelli et al., 2014](#)). Naive whey proteins generally are not very likely to form self-

standing films. Research on films that combine chitosan and whey protein isolate with sodium laurate and modified TiO₂ nanoparticles has demonstrated that adding nanoparticles improves film strength, fosters improved polymer interactions, and lowers water vapor permeability ([Leya et al., 2024](#)).

4.6.2 Gelatin-Based Biopolymer

Gelatin, also known as “warm-water-soluble collagen,” is created by partially denaturing collagen with diluted acids or alkalis, which cleave cross-links and disintegrate the structure ([Kaushik et al., 2016](#)). The amino acid sequence follows the “Gly-X-Y” pattern, with proline occupying the X or Y position and hydroxyproline specific to the Y position ([Djagny et al., 2001](#)). The most common commercial source of gelatin is pig skin (46%), which is followed by bovine skin (29.4%), bones (23.1%), and miscellaneous sources (1.5%). Gelatin has also been extracted from other sources, including sea urchins, fins, bones, and jellyfish ([Ramos et al., 2016](#)). Gelatin has a pale-yellow tint and a vitreous, brittle texture, and is an almost tasteless and odorless substance. It usually has a relative density of 1.3–1.4 and includes 8–13% moisture. Gelatin exhibits several functional properties, including gel-forming, thickening, emulsifying, and foaming capabilities ([Farris et al., 2010](#)). The mechanical properties of gelatin strongly correlate with its supramolecular structure; for example, a decrease in helicity reduces its ultimate tensile strength ([Nagarajan et al., 2019](#)). Gelatin is a biodegradable, non-toxic, and FDA-approved material primarily, which makes it convenient for usage in the food packaging industry ([Gómez-Guillén et al., 2011](#)). Gelatin can be obtained through acid, alkaline, or enzymatic hydrolysis. The gelatin solutions are filtered after these procedures, deionized, and concentrated using membrane filtering or vacuum evaporation techniques ([Nagarajan et al., 2019](#); [Gómez-Guillén et al., 2011](#); [Guo et al., 2003](#); [Arpi et al., 2018](#)).

Gelatin’s ability to form an exterior coating that shields food from oxidation, light exposure, and dryness has been widely used to preserve

food throughout its shelf life. Yet, because gelatin is extremely hygroscopic, it tends to inflate or dissolve when it comes into contact with food surfaces that have a high amount of moisture. Numerous studies have investigated the addition of various materials, including crosslinkers, strengthening agents, plasticizers, and additives with antimicrobial or antioxidant qualities, to improve the functional qualities of gelatin-based films and extend the shelf life of food ([Mellinas et al., 2016](#); [Ortiz et al., 2016](#)). The potential of employing a natural extract as a novel crosslinker for gelatin (Type B, produced from bovine bone) was shown by [Zhao et al. \(2016\)](#). In comparison to untreated gelatin, the modification greatly increased gel strength through hydrogen bonding interactions between water and free hydroxyl groups of amino or polyphenol groups. The modification of gelatin using *Galla chinensis* extract as a natural crosslinker was done. The results showed that the extract enhanced gel strength, thermal stability, and viscoelastic properties of gelatin while reducing its swelling capacity due to a denser network structure. It also modified the gelatin microstructure and strengthened intermolecular interactions, indicating its effectiveness in improving and stabilizing gelatin properties ([Zhao et al., 2016](#)).

Combining gelatin with other biopolymers such as whey proteins, starch, chitosan, or pectin is another method of improving gelatin-based films ([Ramos et al., 2016](#); [Gómez-Guillén et al., 2011](#)). Various types of gelatin have been studied for their functional enhancements through the incorporation of active additives. Fish gelatin, when combined with *Origanum vulgare* L. essential oil, has been utilized in films to improve water vapor permeability (WVP), solubility, and ultraviolet (UV) barrier properties, as demonstrated by [Hosseini et al. \(2015\)](#). Additionally, nano-encapsulation of *Origanum vulgare* L. essential oil in fish gelatin films has been found to maintain initial thermal stability, enhance flexibility, reduce WVP, and exhibit antimicrobial activity ([Hosseini et al., 2016](#)).

Bovine gelatin films containing bacteriocins and flavonoid ester prunin laurate have been shown to retain their functional properties while enhancing antimicrobial activity due to a synergistic effect ([Ibarguren et al., 2015](#)). Similarly, incorporating 10–40 mg of silver nanoparticles (AgNPs)

into gelatin films significantly altered their properties. Color difference (ΔE) rose from 2.1 ± 0.1 to 61.4 ± 0.4 , while transparency (T_{660nm}) decreased from 89.1% to 49.6%. Tensile strength dropped from 35.0 ± 4.7 MPa to 26.3–28.6 MPa, and Young's modulus initially declined to 448.5 ± 24.4 MPa (10 mg) before increasing to 609.6 ± 54.8 MPa (30 mg). Elongation at break ranged from 45.6% to 60.5% without a clear trend. Moisture content slightly increased (11.39% to 13.14%), and water vapor permeability remained stable ($2.92\text{--}3.02 \times 10^{-9}$ g·m/m²·Pa·s). The water contact angle showed minimal change (43.6°–48.5°), indicating minor variation in surface hydrophobicity. Overall, AgNP-based gelatin films notably impacted optical and mechanical properties, with minimal effects on moisture and barrier traits. ([Kanmani & Rhim, 2014a](#)).

When added to gelatin films, zinc oxide nanoparticles improve elongation at break, moisture content, water contact angle, WVP, and thermal stability, in addition to having potent antibacterial properties. Elongation at break (E) improved markedly from $7.3 \pm 0.2\%$ in control to as high as $33.4 \pm 3.2\%$ in Gel/ZnOA, indicating increased flexibility due to disruption of the dense polymer network, allowing the films to stretch more before breaking. Moisture content (MC) also increased, reaching 14.3% in Gelatin/ZnOA and Gelatin/ZnOACMC, compared to 11.1% in the control. Water vapor permeability (WVP) rose from 1.25 ± 0.12 to $2.47 \pm 0.05 \times 10^{-9}$ g·m/m²·Pa·s, and the water contact angle (WCA) improved from 52.4° to a peak of 63.0°, suggesting better moisture interaction and enhanced surface hydrophobicity. Overall, ZnO NPs enhanced the flexibility, water interaction, and barrier properties of gelatin-based films. ([Shankar et al., 2015](#)).

Additional research has examined the antioxidant advantages of other plant extracts; fish gelatin films with extracts of green tea, grape seeds, ginger, or ginkgo leaves show enhanced antioxidant qualities ([Li et al., 2014](#)). Bovine gelatin films infused with brown seaweed (*Ascophyllum nodosum*) increase hydrophilicity and antioxidant activity ([Kadam et al., 2015](#)). Similarly, gelatin films infused with tea polyphenols enhance antioxidant activity ([Wang et al., 2015](#)). However, gelatin has certain

drawbacks, including low strength, brittleness, inelasticity, poor mechanical qualities, limited temperature stability, high moisture sensitivity, and an insufficient moisture barrier ([Ramos et al., 2016](#)).

4.6.3 Casein-Based Biopolymer

Casein, a primary protein in milk, precipitated out of the milk at 4.6 pH. According to research, casein is a protein that is largely unstructured and lacks a clear secondary structure ([Ponce et al., 2016](#); [Saez-Orviz et al., 2017](#)). α S1, α S2, β , and κ -caseins are the four sub-parts of casein, a phosphoprotein that is present in milk. These subfractions influence its ability to form films. Among its many advantageous properties are resistance to chemicals, biodegradability, nontoxicity, binding small particles capacity, and micelle production. Because of these characteristics, casein is a perfect material for creating biodegradable films ([Bonnaillie et al., 2014](#); [Khan et al., 2021](#)). Due to its excellent nutritional value, emulsifying qualities, and water solubility, casein protein is regarded as an appealing biomaterial for the manufacture of films ([Picchio et al., 2018](#); [Khan et al., 2021](#)). The production and demand for casein have increased as food technology develops, and its uses have increased ([Lisitsyn et al., 2021](#)).

Casein can be extracted from skimmed milk by either treating it with rennet to create rennet casein or acidifying it to create acidic casein. After being extracted from the serum, the resultant casein clot is cleaned and dried. It is produced in a different way than non-food-grade casein. Films can be prepared directly from a liquid solution without any additional processing steps. During the formation of films, the percentage of protein used in the formulation significantly affects the compatibility between whey and casein proteins, as it influences the ability to form a stable film ([Wagh et al., 2014](#)). The coagulation method used determines the type of casein obtained, each with distinct characteristics. The primary types are rennet and acid casein ([Carr & Golding, 2016](#)). When milk is acidified with lactic acid or mineral acids, acidic casein, which has a pH of about 4.6 and is

insoluble in water, precipitates ([Chen et al., 2019b](#)). Rannet casein cleaves the κ -casein tail and is likewise insoluble in water. It causes the casein micelles to become unstable ([Picchio et al., 2018](#)). Because polar amino acids are distributed throughout the protein chain, they have excellent barrier qualities against oxygen and other non-polar molecules, which makes them useful for shielding oxidation-prone products ([Chevalier et al., 2018](#)). However, the cohesive film matrix formed by the interaction forces between the polar and non-polar amino acids in the casein structure decreases as it dries, leading to brittleness ([Xu & Gowen, 2019](#)).

As casein is less soluble, caseinate, also known as sodium caseinate, is frequently added to conventional binding molecules. Collagen-based electrospun films that contain isolates of casein, keratin, and soy protein may greatly improve the properties of collagen fibers and aid in the creation of better food packaging materials ([Wu et al., 2019](#)). In a prior study, scientists successfully created composite films using casein and gelatin using a natural crosslinker, gallic acid. They discovered that adding gallic acid improved the film's quality ([Bhatia et al., 2022](#)). According to research, calcium caseinate films are extremely hygroscopic, and their physical properties in a range of environmental settings are essential for developing new applications and optimizing existing ones ([Bonnaillie et al., 2014](#)). Similarly, the impact of iron and casein on oxygen permeability was similar in bilayer-modified films based on polyethylene/polycaprolactone. Tensile strength increased by up to 12%, and elongation decreased by two-fold as a result of the contacts formed, suggesting that new crystallinity had formed in the polyethylene/polycaprolactone-C-Fe05 and polyethylene/polycaprolactone-Fe1 samples ([Rescek et al., 2016](#)). In order to enhance the physicochemical properties and antibacterial activity of casein, tannic acid produced from plants was found to be an efficient crosslinking agent ([Picchio et al., 2018](#)). According to another study, citric pectin-treated calcium-caseinate/glycerol increased the elasticity and strength of casein-based films. The biopolymer's susceptibility to temperature and humidity was also lessened ([Bonnaillie et al., 2014](#)). However, there are certain drawbacks to casein-based films, including their

high moisture sensitivity, pH sensitivity, and water solubility. These elements have a major effect on their interfacial and mechanical characteristics.

4.7 PLANT-BASED PROTEIN AS BIOPOLYMER

Plant-based protein biopolymers refer to sustainable, biodegradable materials made from plant sources, such as soy, wheat, and peas, that may be used to create films or coatings and provide a possible substitute for conventional plastic packaging. The Food and Agricultural Organization reports that the amount of food waste proteins is expected to reach 126 Mt by 2020 ([Senthilkumaran et al., 2022](#)). To utilize the waste and modify it for its usage, protein biopolymers act as a promising alternative to synthetic packaging materials ([Babaei-Ghazvini et al., 2021](#); [Murrieta-Martínez et al., 2018](#)). Numerous protein isolates from defatted pressed foods, such as peanuts and soybeans, have previously been found to be useful as foaming agents, stabilizers, fortifiers, and emulsifiers. Blends of papaya puree and defatted soy protein enhance the films' optical, structural, and mechanical barrier qualities, with the edible film features being particularly noteworthy ([Senthilkumaran et al., 2022](#)). The plant proteins, which are popularly used as packaging material in isolation or combination with other biopolymers, are discussed next.

4.7.1 Soy-Based Protein

Soy protein isolate (SPI) is used to make soy protein-based film, which consists of 11S globulin (~350kDa) and 7S globulin (~200kDa). These films can be utilized in place of synthetic packaging materials and are ecologically benign and biodegradable ([Tian et al., 2018](#)). Additionally, they have high oxygen barrier qualities, which can help packaged goods last

longer on the market. 38–44% of soybeans are made up of protein, which has molecular weights between 200 and 600 kg/mol. The complete protein found in soybean meal satisfies every important amino acid that a person needs to consume ([Leya et al., 2024](#)). Due to their good oxygen barrier properties, they help extend packaged materials' shelf life ([Zubair & Ullah, 2020](#)). The interactions of polar and non-polar side chains of globular proteins improve the soy protein-based films' tensile strength, stiffness, and hardness, which makes them perfect for creating edible and biodegradable films. Soy protein films are primarily made from highly refined soy protein isolate (SPI), which has a minimum protein concentration of 90%. The four categories are differentiated on the basis of ultracentrifugal fractions as 2S, 7S, 11S, and 15S fractions (S stands for Svedberg unit). Incorporating these properties, a blend film made of soy protein isolate and polyvinyl alcohol (SPI/PVA) is a biodegradable possible packaging material. The two components have outstanding oxygen barrier qualities. Materials used for packing must have heat-sealing qualities. The required sealing qualities were achieved by SPI/PVA film when the PVA component was above 15%. The strength of the seal was decreased, though, when glycerol moved to the surface and prevented macromolecular chains from becoming entangled in the sealing interface. When glycerol vaporized at 204°C, the sealing region developed unsightly blistering. Thus, 200°C was the ideal sealing temperature for the blended film ([Tian et al., 2018](#)). Different techniques have been used for the production of soy-based films and their enhancements, like the extrusion technique ([Zubair & Ullah, 2020](#)), SDS+SPI formulation, casting, heating, spinning, thermal compaction, and SPI/nano-silica ([Xu et al., 2019](#)) for extending the shelf life of food products. Currently, the modification of SPI composite films using SNPs has increased the antibacterial activity against pathogenic bacteria ([Alizadeh et al., 2022](#)).

4.7.2 Zein-Based Protein

Zein, an isolate protein found in corn, is a kind of prolamin protein that accounts for 60–70% of the total protein in corn. It is an insoluble, non-toxic, and edible protein commonly used for the development of films and coatings. Non-polar amino acids are present in high amounts, but they lack basic amino acids like tryptophan and lysine, which leads to their unsuitable consumption by humans. The production of films and coatings involves casting the solutions of zein in ethanol, following evaporation of the solvent and the phenomenon of cross-linking of protein ([Moreno et al., 2019](#)). Their applications include coatings on food products like vegetables, fruits, and nuts, as they help preserve them and increase shelf life. Flexible extrusion and moldable stretching are used to make these coated films. The nanocomposites from this plant source are BCN-Zein (bacterial cellulose-Zein nanocrystals) that show better thermal stability (till 400°C) and tensile quality (68.4µm) because of the strong interactions between zein nanoparticles and BCN matrix ([Li et al., 2020](#)). Another composition of zein films includes the loading of 5/10% of ZEO (Zataria multiflora Boiss essential oil ([Kashiri et al., 2017](#)). To inhibit the growth of bacteria, specifically on meat samples, zein mixed with a cocktail of naturally derived antimicrobial agents like thyme oil and nisin is most effective. The combination of zein and chitosan film is considered suitable as a carrier of bioactive compounds for the formation of barriers and to prevent loss of moisture, thus ensuring food quality and prolonged shelf life of fruits ([Shen et al., 2021](#)).

4.7.3 Gluten-Based Biopolymers

Gluten is a rubber-like proteinaceous substance present in wheat, barley, and rye grains. Gluten falls under the category of alcohol-soluble proteins, which can be present in monomeric or polymeric forms, known as gliadin and glutelins. Gluten-based bioplastics are flexible, biodegradable, highly resistant, and environmentally beneficial, with gas barrier properties, and potentially containing no chemical volatiles, and therefore making them less likely to contaminate food ([Bibi et al., 2016](#)). Gluten is extracted from

whole flour by washing flour with water or salt solution that removes particulate matter and soluble substances to leave a proteinaceous mass. This method is widely used by industries for gluten separation as a byproduct of starch-producing industries ([Bathula et al., 2018](#)). After extraction, films are made from gluten by mixing with water and plasticizers to make a dough, which is then flattened and heat-treated to form a thin biofilm ([Gómez-Heincke et al., 2016](#)). Gluten films can be further modified to enhance their packaging potential by adding crosslinking agents and antimicrobial and antibacterial agents. [Türe et al. \(2012\)](#) used potassium sorbate as an ingredient with wheat gluten to create compression-molded films that had good antibacterial qualities and could be used as edible packaging ([Türe et al., 2012](#)). In addition, wheat gluten and nisin were combined to create edible packaging ([Teerakarn et al., 2002](#)). Furthermore, some studies used various additives and chemical agents to increase the mechanical and gas barrier qualities of gluten-based bioplastics ([Peelman et al., 2013](#); [Guillaume et al., 2008](#); [Fernandez-Saiz et al., 2008](#)). Wheat gluten-based bioplastics offer a wide range of uses in the food packaging industry. Incorporation of antimicrobial activities and inhibitory effects by adding certain external agents, such as thyme essential oil, enhances the functional properties of gluten-based biofilms ([Zhu et al., 2022](#)). Along with this, plant phenolic extract enhances the antioxidant properties of gluten-based films ([Khashayary & Aarabi, 2021](#)). Natamycin and rosemary extract are reported to enhance the anti-microbial properties of gluten-methyl cellulose extract ([Türe et al., 2008](#)). However, the use of gluten-based edible films is restricted due to elicited allergic responses in populations with celiac disease ([Xu & Li, 2023](#)). So, there is a need to add certain modifications to the basic structure of the gluten after its extraction from the natural source so that it can be applied to broader food entities for universal applicability. Along with it, gluten-based biopolymer has poor water permeability and mechanical properties. The incorporation of macromolecules, antibacterial and antioxidant agents, and nanofillers can enhance these properties. However, there is a need to establish a large-scale production protocol for efficient gluten-based films.

4.8 UTILIZATION OF PBB IN THE FOOD INDUSTRY

PBBs are utilized for packaging at different sections of the food industry, including dairy products, confectionery, and meat products ([Figure 4.3](#)). These PBBs are derived from different vegetable or animal sources. Some of the vegetable and animal-based protein-based films/coatings used are soy (SPI), zein (Zein-chitosan combo film), casein films, and whey. Researchers first extracted polypeptides from a wide range of animal and vegetable sources or by-products. These are categorized into plant protein-based packages and animal protein-based packages. These PBBs can work in isolation, or they can be combined to address the needs of the food packing industry. Along with it, certain animal and plant sources for PBB that can be utilized in food packaging are under research trials. One such example is *Moringa oleifera* seeds, which are an important source of proteins with good antioxidant activity ([Kumar et al., 2022](#)).

The use of plant proteins in the packaging industry is rapidly growing, and vegan diets can benefit from the use of plant proteins in food packaging, which can offer a number of benefits, including active substances, great variety, and financial sustainability. The addition of these byproducts from plants into protein-based food packages leads to enhanced bacterial protection due to the presence of phenolic compounds as they possess properties like cell wall disruption and enzyme inhibition. Antimicrobial edible coatings and films that include essential oils and natural herbal extracts offer a number of advantages and are regarded as a breakthrough in active biodegradable packaging. Several studies advocate the use of different plant proteins to form stable coating materials. According to a study, a coating made from the mucilage of *Plantago major* seeds and enhanced with essential oil from *Anethum graveolens* inhibited the growth of fungi (*Candida albicans*, *Aspergillus fumigatus*) and bacteria (*E. coli*, *S. aureus*, *S. pyogenes*, *B. subtilis*, and *B. cereus*). This resulted in a

significant reduction in the growth of spoilage microorganisms with increased shelf life of protein-based packages. It demonstrated how the PMSM with diluted essential oil extended the beef’s shelf life by halting microbial spoiling and lipid oxidation. The findings of the microbiological, chemical, and sensory evaluations supported the idea that PMSM+1.5%D wrapping helped beef maintain its high-quality attributes and increase its shelf life while being stored ([Mihalca et al., 2021](#)). The malt spent grain biomass produced during the brewing process is another agro-food by-product with promising reuse potential because of its high protein content, fiber, and phenolic compounds. Given that it is inexpensive and readily available, the proteins from brewer’s spent grains may be a viable substitute for producing biodegradable film with antioxidant properties ([Vieira et al., 2024](#)).

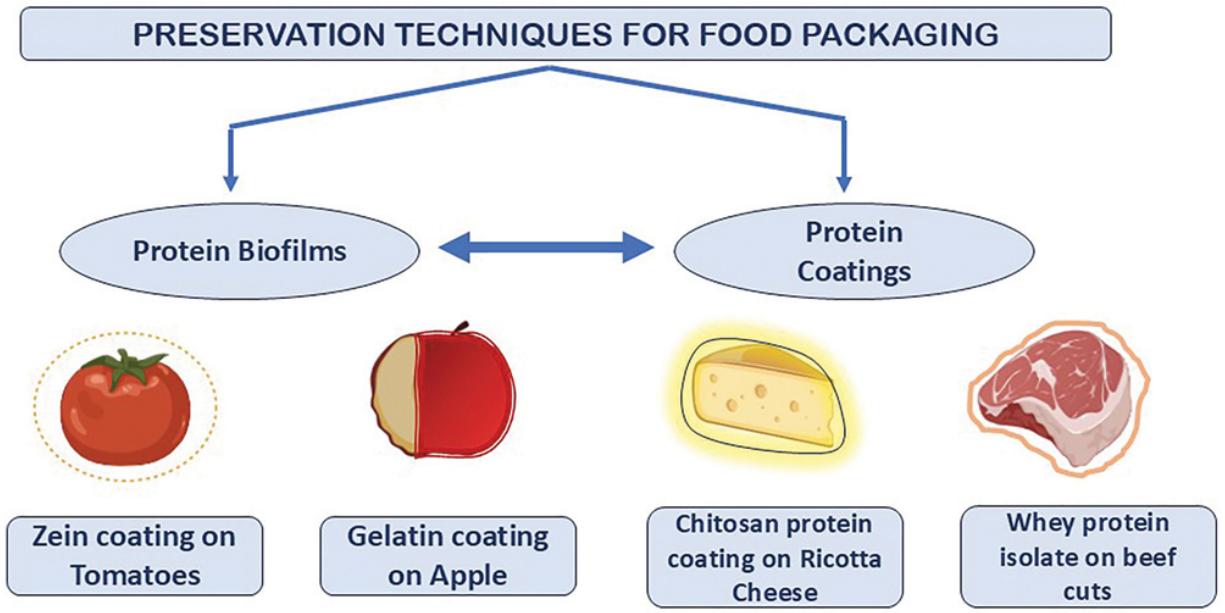


FIGURE 4.3 Broad application of PBB in food packaging industry. ↗

The legume’s resistance to biotic (high capacity to fix atmospheric nitrogen, high seeds, and protein output) and abiotic (dryness, water stagnation, and extremely poor and dry soils) stressors makes grass pea flour extremely economical. Although the enzyme was able to form high molecular weight polymers that were resistant to hydrolysis, digestibility

analysis conducted under physiological conditions showcased that the proteins in grass pea flour were more readily broken down by both duodenal and gastric proteolytic enzymes when the bioplastics were made without mTGase ([Giosafatto et al., 2018](#)). The suspension of grass pea flour can be treated with microbial transglutaminase (mTGase) and a tiny amount of glycerol (8%) as a plasticizer to create edible coatings.

By reducing the particle size, the enzyme treatment somewhat affects the usual protein agglomeration size; nevertheless, the zeta-potential and polydispersity index of the resultant film-forming solution are unaffected by the mTGase treatment. Another kind of edible film was made from an alginate-clay composition by adding essential oils (cumin, coriander, marjoram, cinnamon, clove, and caraway). The antimicrobial activity of the film was assessed on slices of rainbow trout, with marjoram essential oil showing the strongest inhibitory effect, followed by clove and cinnamon essential oils ([Mihalca et al., 2021](#)). Coatings made from soy protein isolate and honey are used to decrease any microbial growth, along with maintaining the taste and color of melons ([Leya et al., 2024](#)). Overall, plant protein provides a solution for future food packaging industries.

Animals act as an important source for the extraction of protein that can be used in the food packaging industry. Animal protein-based packaging addresses the challenge of maintaining food quality for a longer period of time. Color is a crucial aspect of quality since people tend to equate it with freshness when buying meat. Consequently, transparency is a crucial feature of the film used on meat products. Meat products may change color due to bacterial modification. Therefore, it can be beneficial to apply active packages that contain antibacterial compounds (such as essential oils, antibacterial proteins, and nanoparticles). There have been several successful studies where animal proteins were efficiently used to form coatings and films for food packaging; for example, milk proteins can create pliable, translucent, and flavorless films. Whey and casein proteins are two types of milk proteins. These casein films may contain food additives, such as antimicrobials, food coloring, or antioxidants. Aqueous caseinate solutions can be used to create edible casein films, which are then

dried. An edible coating made of whey protein that is infused with antimicrobial chemicals aims to prolong the product's shelf life and prevent the growth of dangerous bacteria. The mesophilic and psychrotrophic counts of ricotta cheese coated with chitosan/whey protein edible film and kept at 4°C for 30 days were significantly lower than those of the control. Edible whey protein concentrate coatings made by heat denaturation or UV irradiation combined with antimicrobials (lactic acid and natamycin) appear to be a viable substitute for commercial coatings in matured cheese ([Meshram et al., 2022](#)).

Fresh fruits, vegetables, and nuts can be preserved by using WP-based films, which are a great moisture barrier to keep them from drying out. They are also used in confectionery and bakery products as a fat replacer, improving texture and mouthfeel. Whey proteins' hydrophilic nature restricts their capacity to function as water vapor barriers despite the fact that they are excellent oxygen barriers at low and intermediate relative humidity levels ([Kumar et al., 2018](#)).

Cheese is a ready-to-eat dairy product that can readily become infected on the outside by harmful microbes, which can lead to spoiling and unpleasant flavors ([Kandasamy et al., 2019](#)). Additionally, some cheese types may experience a number of unfavorable organoleptic changes as a result of increased moisture loss ([Henriques et al., 2016](#)). [Wagh et al. \(2014\)](#) used WP films to preserve Cheddar cheese and discovered that coatings did not affect the goods' qualities or sensory attributes. The goal of an edible WP-based coating that has been injected with antimicrobial agents is to prolong the product's shelf life and stop harmful germs from growing ([Wang et al., 2019a](#); [Ramos et al., 2012](#)). Cheese surfaces were shown to be inhibited by WPI films impregnated with nisin (50 IU/mL), malic acid (3%), sorbitol (1.5%), and natamycin (0.002 g/mL) against *L. monocytogenes*, *Pseudomonas aeruginosa*, *Penicillium commune*, *P. chrysogenum*, and *Yarrowia lipolytica* ([Pintado et al., 2010](#)). The mesophilic and psychrotrophic counts of ricotta cheese coated with chitosan/WP edible film and kept at 4 C for 30 days were significantly lower than those of the control ([Di et al., 2011](#)). When it comes to cheese's

ability to withstand moisture and weight loss, covering it with edible antimicrobials is a suitable substitute for commercial coatings ([Kandasamy et al., 2021](#)).

Moreover, WP coatings in fresh-cut fruits and vegetables can serve as gas or moisture barriers, preventing moisture loss and/or lowering environmental oxygen intake, which in turn lowers the respiration rate ([Milani & Tirgarian, 2020](#); [Khwaldia et al., 2004](#)). Because of biochemical interactions between phenolic chemicals and endogenous polyphenol oxidase that are released, as well as the penetration of ambient oxygen into the tissue, freshly sliced apples frequently change color. Apple and potato slices with edible WP coatings function as oxygen barriers and postpone browning processes ([Wang et al., 2019a](#)). Compared to calcium caseinate, WP seems to have a higher antioxidant capacity ([Tien et al., 2001](#)).

Apple slices coated with WP coating and emulsion film comprising WPI or WPC and beeswax or carnauba wax demonstrated an anti-browning action ([Perez-Gago et al., 2005](#)). Apple browning can be prevented most effectively with WPC and beeswax-based coatings that contain either 0.5% cysteine or 1% ascorbic acid ([Perez-Gago et al., 2006](#)). The RH in the atmosphere can affect how effective WPI coatings are. Internal oxygen levels decreased while carbon dioxide levels rose at lower relative humidity. Because of the decreased oxygen levels (approximately 0.025 atm), coated fruits under lower relative humidity (about 70% to 80%) experienced anaerobic respiration ([Cisneros-Zevallos & Krochta, 2003](#)). So, several successful research trials advocate the usage of whey protein films in food packaging. The most prevalent protein found in the body, collagen, serves a variety of purposes. Collagen is typically utilized with other biopolymers in packaging applications.

The agar-alginate-collagen film with silver nanoparticles used for packaging integration is one example; it has exceptional mechanical and water resistance as well as outstanding antibacterial qualities (against *Escherichia coli* and *Listeria monocytogenes*).

Along with it, gelatin, which is produced by hydrolyzing collagen, is another animal protein that is commonly seen in (edible) food packaging. It

has been demonstrated that films made from bovine gelatin have a hydrophobic surface and that this hydrophobicity is further increased when chitin is added to the gelatin film ([Hanani et al., 2019](#)). Gelatin has been extensively used in combination with various natural and bio-based materials to develop edible films and coatings that enhance its functional properties for food packaging applications. For instance, blending gelatin with chitosan has shown effectiveness in reducing color deterioration in beef steaks by limiting metmyoglobin formation and lipid oxidation, successfully maintaining organoleptic properties during a five-day retail display ([Cardoso et al., 2016](#)). Similarly, combinations with pectin and sodium alginate have been applied in breakfast pork sausages to improve film characteristics ([Liu et al., 2007](#)). Gelatin coatings with different concentrations (0%, 10%, and 20%) significantly preserved pork meat quality during seven days of refrigeration without major color changes ([Davis & Lin, 2005](#)). Moreover, gelatin mixed with kappa-carrageenan and glycerol helped reduce weight loss in dry sausages, offering potential economic benefits ([Tyburcy & Kozyra, 2010](#)). Antimicrobial films using gelatin combined with essential oils like thyme ([Lee et al., 2016](#)), *Thymus vulgaris*, and *Rosmarinus officinalis* ([De Oliveira et al., 2013](#)), as well as commercial agents like Nisaplin and Guardian CS1–50 ([Min et al., 2010](#)), effectively reduced *L. monocytogenes* and *E. coli* in chicken and turkey meats. In fishery products, gelatin-chitosan coatings demonstrated antioxidant activity on rainbow trout ([Nowzari et al., 2013](#)) and antimicrobial effects on cod fillets with clove oil ([Gómez-Estaca et al., 2010](#)). Additional formulations with grape seed extract and Ziziphora clinopodioides extended the shelf life of minced trout fillets ([Kakaei & Shahbazi, 2016](#)), while laurel essential oil improved the preservation of trout under vacuum packaging ([Alparslan et al., 2014](#)). Innovative applications include gelatin blended with red pepper seed protein for tuna meat ([Lee et al., 2016](#)) and shrimp concentrate waste for fish sausages ([Alemán et al., 2016](#)), showing microbial control and improved texture. In salmon preservation, gelatin was combined with lignin ([Ojagh et al., 2011](#)), barley bran protein, and grapefruit seed extract ([H. Y. Song et al., 2012](#)),

and even chicken feather protein with clove oil was used to create antimicrobial packaging for smoked salmon ([N. B. Song et al., 2014](#)). Beyond meat and fish, gelatin-based films are also used on fruits and vegetables such as grapes ([Fakhouri et al., 2015](#)), strawberries ([Fakhouri et al., 2014](#)), and melons ([Poverenov et al., 2014](#)), often combined with materials like starch, glucomannan, garlic juice ([Song, 2014](#)), and various fruit and vegetable processing residues ([Galanakis, 2012](#)). For instance, films made from chia oil capsule waste with added blueberry fiber and extract delayed sunflower oil oxidation ([De Moraes Crizel et al., 2016](#)), and similar effects were observed with beetroot residues in oil packaging, keeping peroxide values within Codex Alimentarius limits ([Iahnke et al., 2016](#)). Combining gelatin with these diverse materials improves mechanical strength, antimicrobial and antioxidant activity, and water vapor resistance, significantly enhancing the shelf life and safety of a wide range of food products.

TABLE 4.1 Applications of Various Types of Protein-Based Biopolymers i Packaging ↩

TYPE OF PROTEIN	PROPERTIES	RECOMBINANT	
		SYSTEM/CROSS- LINKAGE	APPLICATIONS REI

<i>TYPE OF PROTEIN</i>		<i>PROPERTIES</i>	<i>RECOMBINANT SYSTEM/CROSS-LINKAGE</i>	<i>APPLICATIONS RELEVANT</i>
Animal Protein	Collagen	Hydrophilicity, flexibility, tensile strength, low antigenicity, easy absorption, biocompatibility	<i>Escherichia coli</i> , yeast, plants, insect cells	Cast films used for meat products Meat
	Casein	Thermally stable, biodegradable, nontoxic, low oxygen permeability	Gallic acid, calcium, iron,	Electrospun films, composite films, antimicrobial films Pic
	Whey	High tensile strength, flexibility, high water vapor permeability	Essential oils, MMT (montmorillonite)	Hydrogels, WPI, WPC, microcapsules, coatings Tax
	Gelatin	Biocompatible, non-immunogenic, biodegradable polymer, moisture sensitivity, high dissolving rate	CuO nanoparticles, chitosan-gelatin-ZnO nanocomposite film, melanin nanoparticles	Films or coatings used in fruit and vegetable packaging, meat packaging, baking industry L

<i>TYPE OF PROTEIN</i>		<i>PROPERTIES</i>	<i>RECOMBINANT SYSTEM/CROSS-LINKAGE</i>	<i>APPLICATIONS REL</i>
Plant Protein	Gluten protein	Flexibility, high tensile strength, high water vapor transmission rate	Potassium sorbate, nisin, plasticizers, mineral oil, CNF(cellulose nanofillers), CMC (carboxymethyl cellulose), TiO ₂ nanoparticles	food packaging films, coatings, adhesives, perishable foods B
	Soy Protein	High nutritional value, biocompatibility, easy availability, hydrogels for biomedical use	Plants	Soy protein isolate (SPI), edible coating used for strawberries L
	Zein	Superior ability to create films, strong tensile strength, and minimal permeability to oxygen and water vapor	Bacteria, yeast, plants	Edible films and coatings, food packaging L

Overall, PBB, from either plant or animal sources, acts as a suitable option with a wide range of applicability in the food packaging industry. There are several research programs devoted to establishing the role of

these PBBs in packing different food commodities. Some of the successful trials associated with PBB-based food packaging are discussed in [Table 4.1](#).

4.9 LIMITATIONS OF USING PBB IN FOOD PACKAGING

Though promising for biomedical and packaging applications, PBB comes with several disadvantages. First, while biopolymers are typically seen as eco-friendly, they can paradoxically contribute to environmental concerns. For example, if they do not decompose properly, they may lead to environmental pollution, and some forms are not entirely renewable ([Sakthivel et al., 2019](#)). Additionally, improper disposal or production practices may result in contamination of foodstuffs, raising health and safety concerns ([Miserez et al., 2023](#)).

Another key limitation of PBB is its relatively low chemical and physical resistance. This makes them less durable when compared to synthetic polymers, limiting their functionality in certain applications. Furthermore, biopolymers used in packaging require careful formulation to prevent issues such as hygroscopicity and microbial growth. In some cases, antimicrobial agents must be incorporated to ensure product safety, which complicates the production process and can increase costs ([Leya et al., 2024](#)). High costs are another challenge when developing biopolymer-based materials. The complex analysis of their physio-mechanical properties adds financial strain to their development. Additionally, large-scale manufacture of edible films and coatings is challenging due to a lack of knowledge about the equipment, ingredients, and application methods required. Allergic reactions can also be a concern, as certain ingredients, like beeswax, may trigger allergies in sensitive individuals ([Leya et al., 2024](#)). Finally, protein-based edible coatings and films can affect the flavor of the packaged food if applied too thickly, and packaging efficiency is reduced when preparation is not carefully controlled. These drawbacks highlight the need for continued

research and development to overcome the challenges associated with the use of PBB ([Leya et al., 2024](#)).

4.10 CURRENT SCENARIO AND FUTURE ASPECTS OF PBB IN THE PACKING INDUSTRY

4.10.1 Current Scenario

Sustainable packaging material is the current research area for the food industry. Intensive research has been going on for the past decade to come up with a solution for completely replacing synthetic packing material. PBBs are considered reliable and sustainable for packaging due to the advantages associated with them, as discussed earlier ([Mihalca et al., 2021](#)). In recent years, the direct incorporation of multiple proteins into biodegradable hierarchical biomaterials has provided long-term approaches for developing green films and bio-coatings from natural proteins like whey, gelatin, casein, soy, and zein proteins. This PBB forms a barrier that encapsulates the food item, enhances its stabilization and firmness, and restricts the contact of microbes, oxidants, and gases to ultimately increase the shelf life of food items ([Abascal & Regan, 2018](#); [Costa et al., 2018](#)). As discussed in [Section 4.8](#), animal- and plant-based proteins are studied for their properties and usage in food packaging. Each PBB has certain benefits and limitations. For example, gelatin is a promising option for forming films as it increases the shelf life of stored material due to its intrinsic anti-microbial and antioxidant properties. However, before the active utilization of gelatin in food packaging, there is a need to address certain issues, including temperature sensitivity, high dissolving rate, and swelling, which can be resolved by linking with several agents ([Luo et al., 2022](#)). Similarly, whey proteins have acquired popularity in film production as they are edible and biodegradable, allow for the valorization of cheese-making

wastes, have great mechanical qualities and flexibility, and are colorless and odorless ([Ramos et al., 2013](#); [Nascimento et al., 2020](#)). Whey protein isolates (WPI) and whey protein concentrates (WPC) are used to create whey-based films ([Tavares et al., 2021](#)) due to intrinsic properties, including low affinity for non-polar compounds such as oils, aromas, and oxygen, which make them a good option for food packaging. However, they are highly polar, and this can be decreased by crosslinking certain materials. There are challenges associated with using zein for making films as they have poor mechanical properties, including tensile strength and flexibility, which need to be elaborated in research programs ([Nanda et al., 2024](#)).

Soybean-based biomaterials can be prepared in a variety of ways, including paste, granules, gels, and membranes, to help them adapt to various food packaging. Current research programs have designed a combination of SPI (soy protein isolate) and zeins, which provide a straightforward way for altering the diffusion coefficients and, hence, the swelling behavior and nutrient release kinetics of food-protein-based microspheres in simulated gastrointestinal fluids. Microspheres with SPI/zein ratios of 5:5 and 3:7 demonstrated near-zero-order release kinetics in the simulated gastrointestinal environment, indicating their potential utility as delivery systems for nutraceutical ingredients in functional foods ([Chen & Subirade, 2009](#)).

Extraction of these proteins at the laboratory scale is successful, but their implementation on the large industrial scale has come up with multiple drawbacks, including batch-to-batch variability, contamination, and recovery of partially degraded proteins with altered properties ([Aigner et al., 2018](#); [Gauza-Włodarczyk et al., 2017](#)). To address these challenges, biotechnological and bioprocess engineering came up with several approaches to produce protein of interest in abundant quantities with stable desired properties ([Wang et al., 2019b](#); [Chambre et al., 2020](#); [Huang et al., 2018](#); [Werten et al., 2019](#)). Several research groups worked on protein production by using recombinant microorganisms as the production system for PBB ([Que et al., 2018](#); [Ibáñez-Fonseca et al., 2019](#)). Although recombinant proteins have been successfully used to produce protein-based

biomaterials in various research programs, their market acceptability is still limited because of the lack of infrastructure and technology for high-pace scaling ([Davison-Kotler et al., 2019](#); [Borkner et al., 2017](#)). However, advancement in cellular agriculture holds hope for large-scale production of protein-based biomaterials in the future.

4.10.2 Future Perspectives

PBB is at the forefront of developing novel food packaging materials. The emergence of PBB is now broadening our understanding of the significance of utilizing existing natural resources to mitigate the adverse ecological effects of certain conventional materials and to boost the natural resource value. Cellular agriculture is anticipated to become a more popular method of manufacturing protein biomaterials as large-scale fermenter technology advances. Although PBB in food packaging is an active area of research, certain aspects are still not completely addressed, including exploring novel natural resources of protein, active models for large-scale production of PBB ([Purewal et al., 2023](#)), policies to encourage industries to produce PBB, techno-economic analysis of using PBB, long-term carbon and water footprinting, energy investment, consumer acceptance and its overall contribution in mitigating environmental pollution ([Figure 4.4](#)). Till now, animal and plant systems have usually been explored to extract protein reserves, although these are complex organisms, and the extraction of desired protein from such sources is an energy-intensive task. Insects and microorganisms serve as a better option for high-scale protein production. Therefore, there is a need to focus on novel bioreserves for protein production.

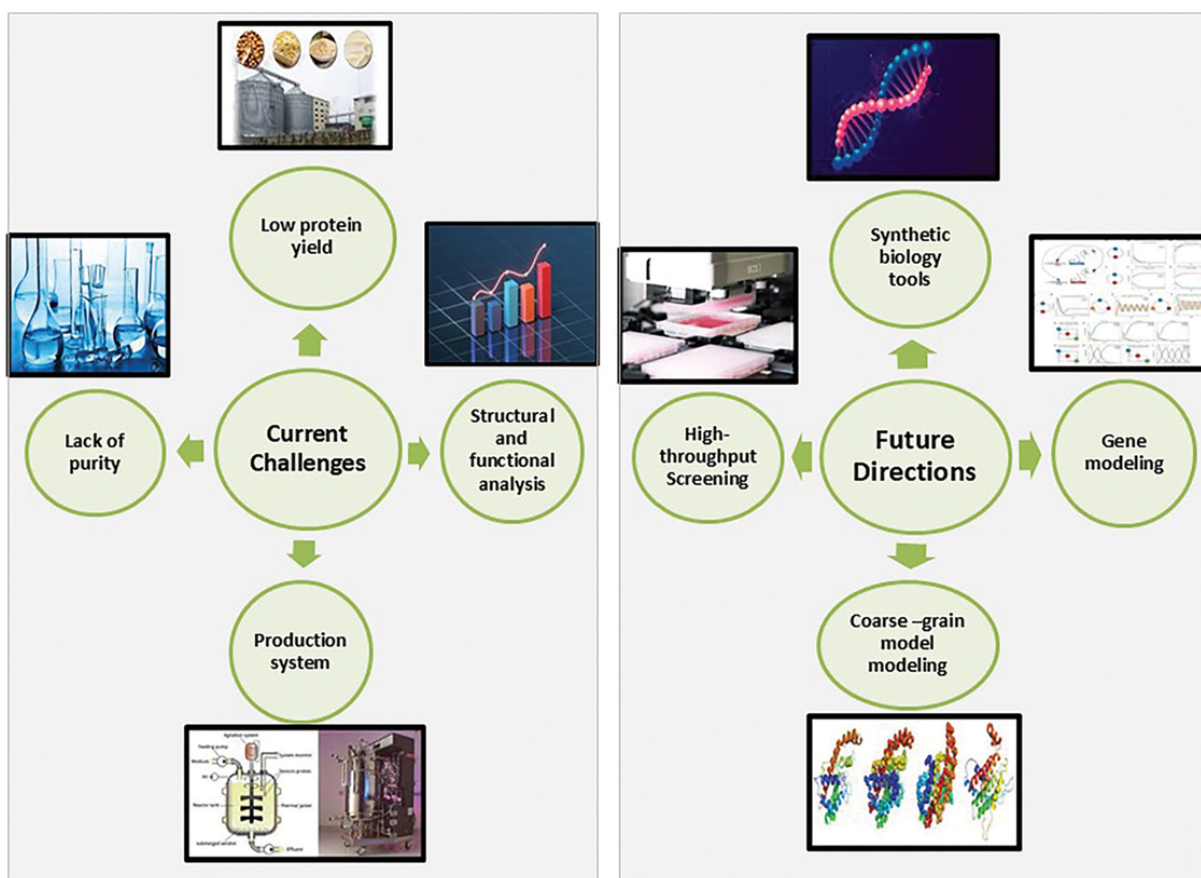


FIGURE 4.4 Current status and future scenario of PBB in food packaging industry. [↗](#)

Along with it, the future holds potential for de novo protein synthesis with desired properties for the particular packaging industry. De novo synthesis helps incorporate synthetic amino acids with desired side groups. These synthetic peptides can be further molded into different 3D architectures, including hydrogels, micelles, multivariant protein aggregates, organic-inorganic structures, and nanoparticles ([Soni et al., 2020](#)). Overall, the perspective of using protein-based biomaterials is that they provide several chances to tune the macroscopic features of materials by changing either the sequence of proteins from which they are derived or the method by which they are processed. In addition to their innate biodegradability and significance in a circular economy, converting waste products into valuable new materials is of inestimable importance. As a result, these PBBs are rapidly advancing and will soon become major solutions to challenges in the food packaging industry.

4.11 CONCLUSION

PBB stands at the forefront of innovative and sustainable biomaterials, poised to revolutionize the food packaging industry by replacing synthetic packaging materials. The versatility of PBB is unmatched, rooted in the protein's precise sequential details and variable folding capacity. The inimitable package of biocompatibility, environmental sustainability, and customization potential makes PBB a reliable option for versatile packaging practices. As of now, research groups can extract proteins from various natural sources and convert them into films and coatings. Along with this, the crosslinking of natural proteins to several other compatible biomaterials has been executed to enhance bioactivity and the usage of PBB. However, the future of PBB centers on the collaboration of interdisciplinary objectives, including bulk production, inertness, high tensile strength, and less energy investment in production procedures. These goals can be achieved by advancing recombinant technologies and collaborating with interdisciplinary fields, including nanotechnology, bioprocess engineering, and data sciences. For instance, data science can generate a roadmap for synthetic biology approaches to create hybrid biopolymers with enhanced thermal and mechanical properties. This approach opens up avenues for next-generation packing material on a laboratory scale. However, the implementation of these small-scale products on an industrial scale needs advancement in bioprocess engineering, including fermentation technology, bioreactor design, and process optimization. The development of cost-effective, environment-friendly methods for large-scale production of protein-based films or coatings will greatly benefit both the consumer and producers. Along with it, the reproducibility and consistency of the PBB are major issues that can be addressed by setting standard production procedures using machine learning and artificial intelligence. Overall, innovation continues to drive the usage of PBB in the food industry, which will be important for the betterment of the environment and consumer health.

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Biomaterials for Active Packaging

5

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5.1 INTRODUCTION

Throughout the whole food chain, food packaging plays an essential part in the modern food industry by extending shelf life and ensuring the quality and safety of food. Serving as a “protective system” for packaged foods, it safeguards food against various external physical (external forces, light exposure, moisture), chemical (pollution sources, adverse reactions with food ingredients), and biological hazard factors (microbial communities) ([Han et al., 2018](#); [Mousavi Khaneghah et al., 2018](#)). With the escalating consumer demands for fresh-keeping, high-quality, safe products, there is an urgent need to develop active packaging. This involves incorporating active functional ingredients into packaging materials to effectively counteract various environmental hazards, thereby prolonging the shelf life of foodstuffs and ensuring their safety and quality ([Ahmed et al., 2022](#)).

In the field of packaging development, conventional petroleum-derived plastics account for approximately 50% of the global packaging market,

with global production reaching 450 million tons in 2022 ([Bergmann et al., 2022](#); [Groh et al., 2019](#); [Rhein & Schmid, 2020](#); [Santhosh et al., 2021](#)). Europe utilized approximately 51.2 million metric tons of plastics, with packaging applications accounting for an estimated 39.9% of this total consumption ([Carina et al., 2021](#)). Commonly used plastics such as polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC) are synthetic polymers that have found extensive applications in our daily lives. The depletion of these petroleum-based non-renewable resources and the ecosystem damages caused by plastic white pollution have raised escalating concerns and presented substantial challenges to environmental governance ([R. Kumar et al., 2021](#); [J. Zhu & Wang, 2020](#)).

Packaging materials derived from biomaterials, commonly known as bioplastics, are usually degradable in natural settings, which helps decrease the volume of plastic waste headed for incineration and reduces the buildup of plastic waste in landfills. Biomaterials have emerged as a viable and sustainable alternative solution to mitigate ecological damage caused by plastic pollution and represent an inevitable future direction. Despite being introduced less than half a century ago, biomaterials have witnessed remarkable advancements characterized by innovative ideas and practical product developments, resulting in a thriving industry valued at around US\$100 billion ([Xue et al., 2021](#)).

5.2 CLASSIFICATION OF ACTIVE PACKAGING

Oxidative spoilage and decay caused by microorganisms have been two major reasons for food quality degradation, restricting the high-quality supply of fresh foods. The development of active packaging provides a new zero-additive, green, safe, and efficient preservation method. The following section provides a detailed overview of the research progress in

antimicrobial, antioxidant, and oxygen-scavenging packaging, focusing on its functional attributes.

5.2.1 Antimicrobial Packaging

The presence of microbial contamination is a major factor that results in food spoilage. Various antimicrobial techniques, such as ultraviolet sterilization, irradiation sterilization, ultra-high-pressure sterilization, and the use of preservatives, have been extensively employed in the food industry. However, these techniques inevitably exert adverse effects on the flavor and nutritional value of processed foods. Developing antimicrobial food packaging aims to establish a system that inhibits pathogenic microorganisms and prevents spoilage proliferation. The antimicrobial function of these materials heavily relies on the interaction between antimicrobial active ingredients and microbial cells. Depending on different mechanisms of action, it can be classified as contact-killing, active release-killing, or photocatalytic oxidation sterilization. According to the different film-forming properties of antimicrobial agents, antimicrobial functional materials can be mainly divided into two types: (1) film-forming polymers with inherent antimicrobial activity as substrates to prepare to package; (2) incorporating inorganic (such as metal nanoparticles, graphene oxide, metal-organic framework organic compounds) or natural extracts and synthetic organic antimicrobial agents (such as essential oils, lauroyl arginine ethyl ester hydrochloride and quaternary ammonium salts, bacteriocins) in biopolymers for fabricating composite film materials with antimicrobial activity.

However, the poor stability of antimicrobial active ingredients and low efficiency limit the wide range of applications for antibacterial packaging. Although excessive use of antimicrobials in food packaging can enhance the antibacterial effect, it can easily cause bacterial stress resistance and affect the flavor and quality of food ([B. P. Kumar et al., 2023](#)). Currently, studies to improve the final antimicrobial activity mainly focus on three aspects: (1) the discovery and application of novel antimicrobial ingredients

in antimicrobial packaging, (2) the construction of a novel film-forming matrix that can provide high permeability and a large specific surface area, and (3) chemical modification of antimicrobial compounds by grafting bactericidal functional groups.

5.2.2 Antioxidant Packaging

The commonly used methods for antioxidant treatment mainly include the addition of antioxidants, vacuum/gas packaging, microencapsulation (fish oil/antioxidants), and antioxidant-active packaging. Currently, adding antioxidants has been the common way to prevent lipid oxidation in food processing, but the potential health risks associated with synthetic antioxidants, as well as relatively poor stability and short duration of action for natural antioxidants, have prompted researchers to develop more efficient and safe antioxidant materials. To overcome these defects, numerous antioxidant food packaging systems have been developed. Broadly speaking, all active materials that inhibit oxidation belong to antioxidant materials, but in most cases, it mainly refers to materials that inhibit the oxidation of free radicals. The antioxidant compounds serve as hydrogen atoms or electron donors. The radical chain reaction can be terminated by hydrogen atom transfer and single electron transfer mechanisms, thereby eliminating free radical activities, including hydroxyl ($\text{OH}\cdot$), superoxide anion ($\text{O}_2\cdot^-$), $\text{ABTS}\cdot^+$, and $\text{DPPH}\cdot$.

Based on the action mode of the active compound, packaging solely with on-site antioxidants and encapsulation of antioxidants with controlled release characteristics have been developed. To enhance the final antioxidant acidity of packaging materials, researchers have explored various factors such as antioxidant functional additives, packaging structures, preparation technologies, and the release behavior of antioxidants on the antioxidant effect ([Kuai et al., 2021](#)). For instance, lower diffusion and release rates of antioxidants in a polymer matrix are desired to extend the action time of antioxidant additive. Cross-linking ([Menzel, 2020](#)), encapsulation of nanoparticles ([F. Liu et al., 2015](#)), and

construction of multilayer systems ([Oudjedi et al., 2019](#)) have shown considerable “barrier effect” to control antioxidant diffusion. Additionally, conventional film-forming techniques (co-extrusion, injection molding, etc.) typically require high-temperature treatment ($>150\text{ }^{\circ}\text{C}$), which often renders heat-sensitive substances inactive.

Antioxidants are key factors in antioxidant functional materials that contribute to their functional properties, and they can be classified into synthetic antioxidants and natural antioxidants. Synthetic antioxidants have been widely used in the food industry due to their abundant availability, low cost, and high efficiency in scavenging activity. However, recent studies have shown potential health risks associated with synthetic antioxidants. The World Health Organization ([FAO/WHO](#)) has reported that excessive or incorrect use of synthetic antioxidants can harm human health. For instance, BHA exhibits a high cytotoxic effect on human astrocytes, leading to disruptions in brain and neural development. Tert-butyl hydroquinone (TBHQ) and its metabolite 2-tert-butyl p-diquinone (TQ) can damage DNA within the nucleus, decrease glutathione levels, increase reactive oxygen species levels, and induce oxidative stress, which may eventually lead to carcinogenicity. In 1997, the U.S. Food and Drug Administration ([FDA](#)) removed BHT from the GRAS (Generally Recognized as Safe) list. The European Union prohibits the use of BHA as an antioxidant in oils and fats; Japan, along with other countries within the European Union, has prohibited the use of TBHQ. Considering the potential safety risks associated with synthetic antioxidants, it is an inevitable trend to seek efficient and safe alternatives for replacing them.

Natural antioxidants can serve as substitutes for synthetic antioxidants due to their safe, non-toxic, and efficient properties. Depending on the type of antioxidant, the primary natural antioxidants utilized in antioxidant activity packaging encompass vitamins (e.g., Vitamin E), polyphenols, and polypeptides (e.g., algal biopeptides, fish protein-derived antioxidant peptides), as shown in [Figure 5.1](#). Currently, polyphenol antioxidants exhibit the highest prevalence and diversity among all antioxidant components, which include flavonoids (e.g., quercetin, rutin), stilbene

derivatives (e.g., resveratrol, pinosylvin), and phenolic acids (e.g., gallic acid, tea polyphenols).

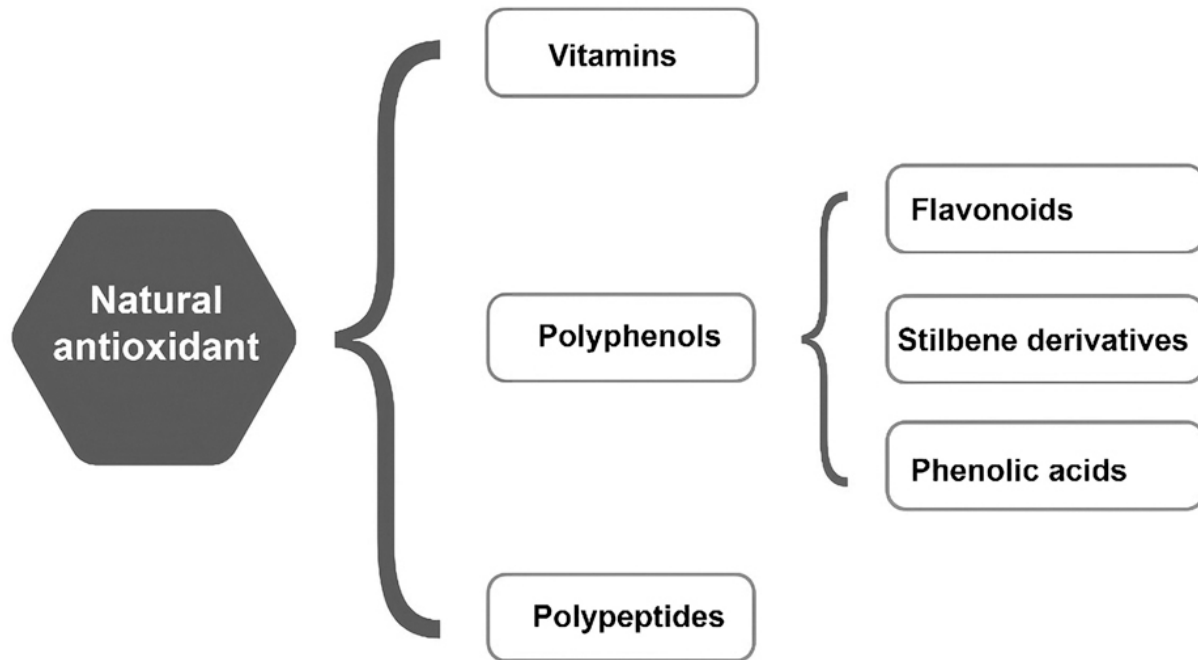


FIGURE 5.1 Classification of natural antioxidant. [↩](#)

5.2.3 Oxygen-Scavenging Packaging

Oxygen is an environmental hazard factor for the preservation of oxygen-sensitive food, as it can lead to sensory quality deterioration, such as discoloration, texture alteration, and off-odor flavor by promoting aerobic microbial growth, lipid oxidation, enzymatic browning, and other pathways. Furthermore, excessive consumption of oxidized food has the potential to harm consumer health due to the generation of secondary byproducts such as 4-hydroxy-2-nonenal and acrolein during the oxidation process of highly unsaturated fatty acids that have been proven toxic at both animal and cellular levels and are considered potential carcinogens. To address these issues, maintaining an oxygen-free atmosphere in packaging environments throughout the processing, transportation, and storage stages is a pivotal strategy to enhance shelf life, preserve food quality, and ensure the safety of oxygen-sensitive food products. Oxygen-scavenging active packaging

shows promising potential to safeguard food products that are vulnerable to oxidation by eliminating dissolved oxygen or the oxygen present in the packaging's headspace ([Kordjazi & Ajji, 2022](#)). The market for oxygen scavengers attained a valuation of US\$2.41 billion by the year 2022, exhibiting an annual growth rate of 5.1% from 2017 to 2022 ([Gaikwad et al., 2018](#)). In order to meet the substantial market demand for oxygen-scavenging packaging, innovative methods have been carried out to prepare highly efficient oxygen-scavenging materials.

The oxygen-scavenging active packaging is mainly fabricated by encapsulating inorganic oxygen-scavenging agents (such as iron and sulfite) and organic oxygen-scavenging agents (including enzymes and phenolic acids) into polymer matrices or by fabricating the packaging using oxygen-scavenging polymers. Various studies explored the incorporation of iron-based oxygen scavengers, enzymatic oxygen scavengers, and phenolic compounds as oxygen-absorbing agents into bio-based films on the preservation of oxygen-sensitive foods (di [Giuseppe et al., 2022](#)). In recent years, oxygen-scavenging active packaging has drawn growing attention due to its numerous advantages, including ease of use, versatile applications, and high efficiency in oxygen removal ([Al Helal et al., 2023](#); [Lee et al., 2018a,b](#); [Wong et al., 2017](#)). [Table 5.1](#) lists the classification, mechanism, and limitations in the practical implementation of commonly reported oxygen-scavenging agents. Currently, the majority of polymers possessing oxygen scavenging capability primarily consist of allyl hydrogen bonds within their molecular structure in the presence of transition metal catalysts (such as 1, 4-polybutadiene, 1, 2-polybutadiene, and norbornene base films); however, these polymers generally lack biodegradability ([Wang et al., 2020, 2019](#)). The availability of biopolymers exhibiting inherent oxygen-scavenging activity is limited. The preparation of oxygen-scavenging packaging using biopolymers primarily involves incorporating oxygen-scavenging agents to fabricate composite films. The following section presents the research progress of oxygen-scavenging active packaging based on the classification of oxygen-scavenging agents.

TABLE 5.1 Classification, Mechanism, and Limitations in the Practical Implementation of Oxygen-Scavenging Agents [↗](#)

CLASSIFICATION	MECHANISM	LIMITATION	REF
Iron-based oxygen scavenger	$\text{Fe}(\text{OH})_2 + \text{O}_2 \rightarrow \text{Fe}(\text{OH})_3 + \text{H}_2\text{O}$	Activity depends on relative humidity; easy to leak; short duration	Bhatia et al., 2011
Sulfite-based oxygen scavenger	$2\text{Na}_2\text{SO}_3 + \text{O}_2 \rightarrow 2\text{Na}_2\text{SO}_4$	Activity depends on relative humidity	Lecourt et al., 2011 Bhatia et al., 2011
Enzymatic oxygen scavenger (e.g., glucose oxidase, laccase)	As a catalyst to accelerate the oxidation reaction rate	Sensitive to relative humidity, pH, and temperature	Johnson et al., 2009
Phenolic acid-based oxygen scavenger (e.g., alpha-tocopherol, pyrogallol, ascorbic acid, gallic acid)	The hydroxyl and enediol groups, which are strong reducing agents, undergo oxidation-reduction reactions with oxygen	Transition metal catalysts are required and show toxicity	Alam et al., 2011 P. K. et al., 2011 et al., 2011
Unsaturated polymer (e.g., hydroxyl-terminated polybutadiene,	The allyl hydrogen bonds as reactive unsaturated hydrocarbons to react with oxygen molecules to form peroxy (ROO•) and alkoxy (RO•) free radicals	Transition metal catalysts are required and	Juares et al., 2011 Wang et al., 2011

<i>CLASSIFICATION</i>	<i>MECHANISM</i>	<i>LIMITATION REF</i>
1.2- polybutadiene)		show toxicity

5.2.4 Iron-Based Oxygen-Scavenging Agents

Iron-based oxygen scavengers are the most widely used preservatives in food packaging. The incorporation of oxygen-scavenging films containing iron-based oxygen scavengers has been extensively investigated. The remarkable reducibility of the $\text{Fe}(\text{OH})_2$ component is primarily utilized to react with oxygen at room temperature, resulting in the production of $\text{Fe}(\text{OH})_3$ and OH_2O , thereby achieving the objective of oxygen consumption and creating a low-oxygen internal environment for packaging purposes. Despite their excellent capacity for consuming oxygen, the oxidation reaction of iron-based oxygen scavengers is highly dependent on the relative humidity of the surrounding environment; only when the relative humidity exceeds 75% can they exhibit their anticipated effect on oxygen consumption. After 15 days of storage at 8°C, fresh-cut apples packaged with a film containing iron-based oxygen scavenger exhibited a lighter color and lower oxidation degree compared to the control group ([Jeong et al., 2024](#)). In a study conducted by Galotto et al. ([Galotto et al., 2009](#)), the oxygen-scavenging capacity of three different forms (film, sheet, and particles) of the same iron-based oxygen-scavenging material was compared. Under conditions of 25 °C temperature and 100% relative humidity, the iron-based oxygen scavenging film exhibited a maximum oxygen scavenging rate of 19.74 ± 0.23 mL/day, which was found to be higher by 8.7% and 8.6% compared to that observed for the iron-based oxygen scavenging sheet and particles, respectively.

5.2.5 Enzymatic Oxygen-Scavenging Packaging

In enzymatic oxygen-scavenging packaging, enzymes act as biocatalysts to accelerate the rate of oxidation reaction, thereby achieving the purpose of reducing the concentration of oxygen. For instance, glucose oxidase can catalyze the conversion of glucose into D-gluconic acid and generate hydrogen peroxide in the presence of oxygen, thereby facilitating rapid oxygen consumption. This oxygen-scavenging capability has rendered it highly appealing for applications in food preservation, biomedicine, environmental protection, and other domains. In addition to glucose oxidase, other oxygen-scavenging enzymes commonly employed include laccase, oxalate peroxidase, and catalase. For instance, laccase exhibits the ability to facilitate the one-electron oxidation of phenol hydroxyl groups into phenoxy radicals while simultaneously reducing oxygen to water, thereby effectively diminishing the oxygen content. Experimental findings demonstrated that a film (2 dm²) incorporating laccase reduced the oxygen concentration from 1% to 0.3% (in a synthetic gas composed of 99% N₂ and 1% O₂) after being subjected to an environment with 100% relative humidity for six days. Conversely, the control sample lacking laccase exhibited negligible alterations in its oxygen concentration throughout the storage duration. Wong et al. mixed hydrophobically modified glucose oxidase with vinyl acetate and then cast it on the inside of a glass bottle to obtain a homogeneous oxygen-scavenging polymer coating with an enzyme content of 0.553 µg/cm detected at the coating interface ([Wong et al., 2017](#)). In a closed glass bottle system (50 vol% headspace, 50 vol% citrate buffer, pH 3.5), the coating effectively reduced headspace oxygen by 2% over eight weeks.

5.2.6 Phenolic Acid Oxygen-Scavenging Packaging

Phenolic acids, being natural, safe, and non-toxic in nature, present themselves as ideal alternatives for iron-based oxygen-scavenging agents. Phenolic acids contain strong reducing groups, such as hydroxyl and enediol groups, which can undergo Redox reactions with oxygen under the catalysis of transition metal compounds like iron and cobalt. This process

leads to the consumption of oxygen inside food packaging. Currently, commonly reported phenolic acid oxygen-scavenging agents include α -tocopherol, pyrogallol, ascorbic acid, and gallic acid. Promsorn et al. present a novel approach for the development of thermoplastic starch/polyethylene films loaded with pyrogallol ([Promsorn & Harnkarnsujarit, 2022](#)). The oxygen uptake capacity of these films, incorporating 1–10% pyrogallol (PG), ranged from 5.0 to 13.1 mL O₂/g. Furthermore, an increasing trend in the maximum oxygen uptake was observed as the storage temperature increased. This study provides evidence that the PG-loaded casting films effectively absorb residual oxygen within sealed packaging.

The application of oxygen-scavenging packaging materials has been employed in the preservation of fresh meat, poultry, dairy products, and fruits and vegetables, effectively inhibiting microbial growth and extending the shelf life of food. However, it currently faces significant challenges in developing highly efficient and safe oxygen-scavenging packaging materials. It is noteworthy that iron-based oxygen scavengers, phenolic compounds, and enzymatic oxygen scavengers are commonly sensitive to the external environment, leading to a substantial decrease in their oxygen-scavenging activity during practical applications. In future research endeavors, further exploration can be conducted to enhance the stability of oxygen scavengers during processing to ensure their long-term effectiveness across different processing methods. Additionally, safety concerns regarding cytotoxicity caused by the precipitation of inorganic nanoparticles, as well as toxicity associated with transition metal catalysts, should not be overlooked when developing functional materials.

5.3 CLASSIFICATION OF BIOMATERIALS FOR ACTIVE PACKAGING

According to the various sources of raw materials, biomaterials for active packaging can be mainly classified into three categories, as shown in [Figure 5.2](#):

- i. Natural source-derived biomaterials or their derivatives, which include polysaccharides, proteins, and lipids.
- ii. Chemical synthetic biodegradable polymers derived from petroleum or biomass, such as poly (butylene adipate-co-terephthalate) (PBAT), poly (caprolactone) (PCL), poly (vinyl alcohol) (PVA), and polylactic acid (PLA).
- iii. Microorganism-synthesized biomaterials, which include polysaccharides (such as bacterial cellulose, pullulan, kefiran, and levan), polyamides (ϵ -polylysine (ϵ -PL), γ -polyglutamic acid (γ -PGA)), and polyesters (such as Poly (3-hydroxyalkanoates) (PHAs) and poly (β -malate)).

[Table 5.2](#) summarizes the application of active packaging incorporating biomaterials in food preservation.

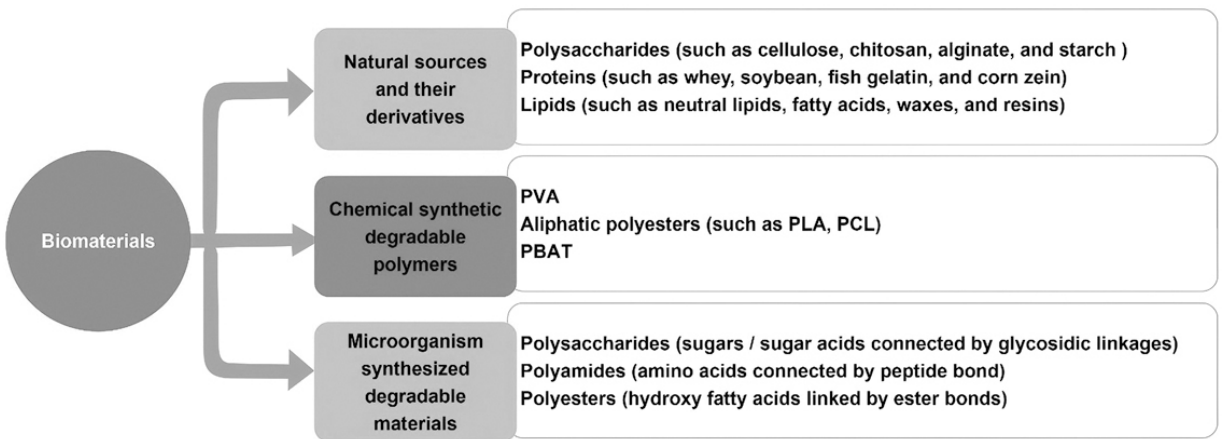


FIGURE 5.2 Classification of biomaterials for active packaging. [↗](#)

TABLE 5.2 Application of Active Packaging Incorporation of Biomaterials

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
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<i>ACTIVE INGREDIENT</i>		<i>POLYMER</i>
Polysaccharides	Anthocyanins	Cassava starch
Pumpkin residue extract/oregano essential oil		Cassava starch
Cellulose nanocrystals/two grape pomace extracts		Tapioca starch
Fennel (Foeniculum vulgare Miller) essential oil		Potato starch/nano zinc oxide
Gallic acid		Hydroxypropyl methylcellulose/polyethylene oxide
Litchi shell extract/halloysite nanotubes		Guar gum/carboxymethyl cellulose

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Cellophane developed by periodate oxidation	Dialdehyde cellophane
β -cyclodextrin/cinnamaldehyde	Shrimp shell chitin/polyvinyl alcohol
Oregano essential oil	The Konjac glucomannan
O-quaternary ammonium chitosan	PVA
Chitosan	PLA/carbon nanotubes
Lepidium sativum (garden cress) seed extract	Sodium alginate

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Sodium alginate	Lily polysaccharide
Starch	PVA
Starch	Chitin/cellulose
Thyme essential oil	Cornstarch
Cellulose nanocrystals	Chitosan

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Golden mushroom foot polysaccharide	Chitosan
Hydroxybenzaldehyde derivatives	Chitosan
Ethyl cellulose modified by rosin-based quaternary ammonium salt	Ethyl cellulose
Pectin crosslinked with citric acid/tartaric acid	Pectin
Sardinella protein isolate	Chitosan
Cinnamaldehyde/ thymol	Gelatin/zein
Antioxidant compounds derived from green coffee oil	Carboxymethyl cellulose

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
by-products	

Mustard seeds	Cellulose acetate
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Nitrogen, phosphorus-doped green-tea-derived carbon dots	Chitosan/starch
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Proteins	Wheat gluten	Lignocellulose from birch powder
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Nisin	Linear low-density polyethylene (LLDPE)
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<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Nisin	Zein
Nisin	Chitosan/nano-cellulose
HX-12C	Chitosan
Lactoperoxidase	Chitosan
Lactoperoxidase	Polyamide
Lysozyme	Polyethylene
Lysozyme	Carboxymethyl cellulose/gracilaria chouae polysaccharide

<i>ACTIVE INGREDIENT</i>		<i>POLYMER</i>
Lysozyme (from hen egg white)		Zein
Lysozyme (from egg white)		Gelatin
Lysozyme		PLA
Lipids	Bees wax	Hydroxypropyl methylcellulose
Lauric acid		Low-density polyethylene (LDPE)
Candelilla wax		Carboxymethyl cellulose

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Candelilla wax	Whey protein
Carnauba wax/ grapefruit seed extract	Carnauba wax
Carnauba wax/ oregano essential oil	Chitosan

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Chitosan/caseinate	PLA
Ginger oil/lime peel oil	PBAT/PLA
Nitrite	PBAT/thermoplastic starch
P-coumaric acid/ layered double/lignin nanoparticles	PVA
Gallic acid	Low-density polyethylene
Carvacrol/citral/ α -terpineol	PBAT/PLA

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Amaranthus leaf extract	PVA/gelatin
Palladium	PET/SiO _x
Thymol	Sodium alginate
Citric acid/tartaric acid	Sodium alginate
Anthocyanin extract from <i>Oxalis triangularis</i> ssp; Linalool	Oxidized sodium alginate cross-linked carboxymethyl chitosan; gelatin/zein
Vitis vinifera grape seed extract	Pullulan/bioactive pectin

<i>ACTIVE INGREDIENT</i>	<i>POLYMER</i>
Carvacrol	Pullulan/chitosan
The extracts of <i>Broussonetia papyrifera</i> fruits and leaves	Pullulan/gellan gum
Quinic acid and montmorillonite	Pullulan/chitosan
ϵ -Polylysine	Chitosan/dialdehyde starch/polyvinyl alcohol double-layer
ϵ -Polylysine	Sodium alginate

ACTIVE INGREDIENT

POLYMER

ϵ -Polylysine and ferulic

Konjac glucomannan

5.4 BIOMATERIALS DERIVED FROM NATURAL SOURCES AND THEIR DERIVATIVES

5.4.1 Polysaccharides

Polysaccharides are a class of naturally occurring macromolecular polymers, typically formed by the linkage of more than 10 monosaccharide units through glycosidic bonds. These polymers can form either linear or branched chains and possess molecular weights ranging from tens of thousands to millions ([Y. Yu et al., 2018](#)). Due to their excellent biodegradability, high biocompatibility, safety, and non-toxicity, polysaccharides have gained increasing attention as raw materials for the development of active packaging, aiming to achieve “zero addition of preservatives” and enhance the quality of food preservation ([Bangar et al., 2023](#); [Carina et al., 2021](#); [Hanani et al., 2019](#); [Yang et al., 2019](#); [F. Zhu, 2021](#)). Considerable efforts have been made to utilize natural polysaccharides with film-forming properties or as active functional ingredients in developing active packaging.

5.4.1.1 Polysaccharides with Film-Forming Properties

Typical polysaccharides such as cellulose, starch, chitin, chitosan, gelatin, pullulan, guar gums, glucomannan, xanthan gum, agar, carrageenans,

pectins, alginates gellan, curdlan, dextrans, arabinoxylans have been widely used as a film-forming matrix, providing the basic physical properties required for packaging.

- **Starch**

Starch-based packaging shares similarities with conventional packaging in addressing the challenge of extending product shelf life; however, it does not inherently prevent food quality deterioration. Incorporating functional agents into starch-based materials can enhance food quality and extend the shelf life of food, which has been a future development trend and has received extensive research attention in recent years. At present, the development of active packaging mainly focuses on two aspects: antimicrobial and antioxidant active packaging. Several starch-based active packaging films have been developed by incorporating metal nanoparticles, metal oxides, essential oils, polyphenol-rich antioxidant extracts from plants, or food processing by-products ([dos Santos Caetano et al., 2018](#); [Monroy et al., 2024](#); [Navaf et al., 2023](#); [Piñeros-Hernandez et al., 2017](#)). Qin et al. prepared antioxidant and pH-sensitive active and intelligent packaging films based on cassava starch and anthocyanins from *Lycium ruthenicum* (LRA) ([Yan Qin et al., 2019](#)). With the increase of LRA content from 1 to 4 wt%, the WVP values of starch-LRA films decreased from 1.13 to $0.97 \times 10^{-10} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}$. A higher ultraviolet-visible light barrier was obtained due to the good UV absorption of the phenolic compounds. This pH-sensitive active film shows promise in monitoring the freshness of pork. Tapioca starch active nanocomposite films by incorporating cellulose nanocrystals and two grape pomace extracts, which exhibited a stronger antibacterial effect against *S. aureus* ATCC 29213 compared to *L. monocytogenes* ATCC 7644 and can prevent *L. monocytogenes* from proliferating on meat samples during a 10-day storage period at 4°C ([Y. Xu et al., 2018](#)). Deshmukh et al. utilized waste extract from litchi shells (LSE) as a natural antioxidant and incorporated it with guar gum

and carboxymethyl cellulose as the polymeric matrix, which was further reinforced with halloysite nanotubes (HNT) via the solution casting method ([Deshmukh et al., 2022](#)). The incorporation of LSE (1, 3, 5, 10, and 20 wt%) into guar gum/carboxymethyl cellulose (GG/CMC) films caused a reduction in the tensile strength of the film but enhanced the elongation at break from 29.93% to 62.12%. Furthermore, the antioxidant capacity of all GCH/LSE blends was significantly enhanced, rising from 9.46% to 91.52%, which represents an increase of more than 10 times in comparison to the pure GCH film. This study demonstrates a sustainable approach to utilizing litchi shell biomass by developing functional antioxidant starch-based packaging materials.

- **Cellulose**

Cellulose is one of the most abundant sources of plant polysaccharides derived from wood, cotton, hemp, and other plant-based materials ([He et al., 2023](#)). In contrast to non-degradable plastics, cellulose is a renewable and biodegradable polymer, and the films made of cellulose demonstrate superior barrier performance, high optical transparency, and robust mechanical properties. Based on the aforementioned unique advantages, cellulose and its derivatives as film-forming matrix have attracted great attention in replacing petroleum-based polymers to develop active biopolymer-based packaging. To offer cellulose-based packaging functionality, strategies such as the grafting of active antibacterial groups onto the cellulose chain, encapsulation of essential oils or other plant-derived active ingredients, and UV-assisted surface immobilization of bioactive agents have emerged as methods in bioactive packaging design. A recent study has found that photo-bactericidal cellulose-based nanofillers can be used as a promising alternative approach to traditional antimicrobial agents for the elimination or reduction of bacteria ([Koshani et al., 2021](#)). In this study, a novel form of hairy nanocellulose, modified with a high density of primary amine groups, referred to as hairy aminated nanocrystalline cellulose (ANCC), has been developed. Rose bengal

(RB), which serves as a natural photosensitizer, was subsequently attached to ANCC through a covalent linkage using an aqueous-based bioconjugation reaction. The RB-ANCC conjugate was incorporated into anionic carboxyl-modified cellulose (CMF) films and the corresponding formulation of nanofibers. The antibacterial activity of photoactive CMF films and nanofibers incorporated with RB-ANCC (2.5 wt%) was assessed by the plating assay and the disc diffusion assay. The results show that light-treated CMF films reduced the number of *L. monocytogenes* by approximately 100% (corresponding to a 6 log reduction), while the nanofiber formulation reduced it by approximately 80%. Additionally, a decrease of *S. Typhimurium* cell counts was approximately 70% for CMF films and approximately 60% for nanofibers when exposed to light. The variation in the antibacterial characteristics between CMF films and CA nanofibers mainly stems from distinct methods of incorporating RB-ANCC. Gao et al. developed an antimicrobial dialdehyde cellophane (DACP) by periodate oxidation ([Gao et al., 2022](#)). This study examined how the concentration of NaIO₄ and the reaction duration (2, 4, and 6 h) affected the aldehyde content of DACP. After incubating *S. aureus*, MRSA, *S. epidermidis*, and *S. pyogenes* with DACP for 12 and 24 hours, no bacterial colonies were observed on the agar plates. The DACP compounds demonstrated remarkable antimicrobial efficacy against gram-positive bacteria at a concentration of 10⁶ CFU mL⁻¹, with the inhibitory effects persisting for up to 24 hours. In addition to serving as a film-forming material, cellulose also functions as nanofillers in the form of cellulose nanowhiskers, nanofibers, and microcrystalline cellulose to modify bulk polymers, thereby enhancing the mechanical and barrier properties of the composite final film.

- **Chitin**

Chitin is the second-most abundant biopolymer in nature after cellulose, widely found in the exoskeletons of shrimp, crabs, insects, and other crustaceans, as well as in the cell walls of fungal organisms ([Qian et al., 2022](#)). It consists of N-acetyl-D-glucosamine monomers

linked by β -1,4-glycosidic bonds, forming a polysaccharide with inherent antimicrobial properties. Despite its abundance, chitin extraction from seafood waste is relatively costly, and the resultant material exhibits limited antimicrobial and mechanical performance. To address these limitations, various pretreatment methods and composite film preparation techniques have been explored to enhance its antimicrobial applications in active packaging. In addition, chitin nanomaterials, including chitin nanofibers and chitin nanowhiskers extracted from the exoskeletons of crustaceans such as crabs and shrimp, exhibit significant potential for use as nanofillers in food packaging. These materials can enhance the barrier and mechanical properties of composite active films. Qian et al. reported an environmentally unfriendly process involving liquefied ball milling to extract chitin (LBSC) from shells and prepare chitin/PVA films containing different concentrations (0, 1, 2, 3, 4, 5 wt%) of β -cyclodextrin/cinnamaldehyde (β -CD/CA) inclusion complexes for controlled release of cinnamaldehyde as a synergistic antimicrobial agent ([Qian et al., 2022](#)). The blend film with 3 wt% β -CD/CA/LBSC/PVA demonstrated maximum mechanical properties, achieving a tensile strength of 41.5 MPa and an elongation at break of 810%, which are higher than that of the 0% β -CD/CA/LBSC/PVA blend film (485%, 31.9 MPa). Following 15 days of incubation with three commonly studied bacteria, including *S. aureus* and *B. subtilis*, as well as *S. typhimurium*, the 3% β -CD/CA/LBSC/PVA film continued to exhibit remarkable antibacterial properties, whereas the inhibition zone of the 3% CA/LBSC/PVA film had nearly vanished, indicating β -CD/CA/LBSC/PVA exhibited prolonged antimicrobial effects. TEMPO-oxidized chitin nanocrystals (TOCN), a type of nanochitin obtained through the TEMPO oxidation process, also possess emulsion-stabilizing properties ([J. Xu et al., 2023](#)). To address the issues of poor stability and unpleasant odor associated with oregano essential oil (OEO) in active packaging applications, TOCN was employed to stabilize Pickering emulsions for encapsulating this

antimicrobial agent. The resulting emulsion was incorporated into a Konjac glucomannan (KGM) matrix at varying ratios (0%, 20%, 30%, and 40%) to develop an active food packaging film. The pure KGM film had tensile strength and elongation of 33.91 ± 3.39 MPa and $45 \pm 3.29\%$, respectively. The addition of OEO Pickering emulsion significantly ($p < 0.05$) decreased the mechanical properties and increased the water vapor permeability, with the value increased from 8.71 ± 0.15 to 15.20 ± 0.55 (g·mm/m²·day·kPa). Furthermore, this film exhibited enhanced antioxidant and antimicrobial properties, which were primarily dependent on the concentration of the incorporated emulsion.

- **Chitosan**

Chitosan, derived from the deacetylation of chitin, is composed of 2-amino-2-deoxy-D-glucose linked by β -1, 4 linkages. Chitosan possesses broad-spectrum antimicrobial properties primarily attributed to its multiple positively charged amino groups that interact with negatively charged groups on the surfaces of fungi, bacteria, and viral cells. The interaction between these biopolymers and microbial cells can alter the membrane fluidity and permeability of the cells, block nutrient entry into the cells, interfere with DNA replication and transcription, as well as inhibit mRNA synthesis, ultimately leading to cell death. In addition to its antimicrobial function, chitosan also exhibits various biological activities such as hemostatic effects, anti-tumor properties against Alzheimer's disease, immunomodulation capabilities, and wound-healing abilities. Due to its excellent biocompatibility, biodegradability, low cost, and wide availability, chitosan has found extensive applications in active packaging, drug delivery systems, and wound healing. However, due to strong intramolecular hydrogen bonding and crystallinity within the chitosan microstructure, it suffers from poor solubility in common organic solvents. Furthermore, although chitosan has a strong bactericidal effect on gram-negative bacteria, it shows relatively poor antimicrobial activity against gram-positive bacteria. To address these issues, surface

chemical modification techniques such as carboxylation, alkylation, acylation, esterification, quaternary ammonium modification, and glycosylation have been reported to enhance the antibacterial and solubilizing properties of chitosan. Zhang et al. reported a method to develop a porous nanofibrous film composed of O-quaternary ammonium chitosan (O-HTCC)/PVA, in which chitosan was modified through covalent bonding of highly positively charged quaternary ammonium groups to improve antibacterial effectiveness ([Z. Zhang et al., 2024](#)). Through the utilization of surface modification techniques and the design of a nano-porous structure to improve reactive activation, O-HTCC/PVA nanofibrous films have shown excellent antibacterial performance against *Escherichia coli* (~86.34%) and *Staphylococcus aureus* (~99.99%).

5.4.1.2 Polysaccharides without Antioxidant or Antimicrobial Potential

Apart from the polysaccharides with film-forming properties, some polysaccharides, such as garden cress extract, olive leaf polysaccharide, and lily polysaccharide, which possess inherent antioxidant or antimicrobial activities, have been used in developing active packaging formulations to offer materials with additional functionalities ([Alkahtani et al., 2020](#); [Alshehri et al., 2024](#); [Cui et al., 2022](#)). *Lepidium sativum* (garden cress) extract showed antibacterial activity against both *E. coli* and *S. aureus*, with minimum inhibitory concentrations of 1.06 mg/mL and 0.56 mg/mL, respectively, and exhibited concentration-dependent effects ([Alkahtani et al., 2020](#)). It also exhibited significant antioxidant activity arising from its phenolic compounds. The garden cress extract was found to contain six phenolic compounds, with gallic acid and chlorogenic acid being particularly prominent. Azizah et al. reported a method for integrating freeze-dried garden cress extract into sodium alginate films ([Alshehri et al., 2024](#)). The incorporation of garden cress extract at concentrations of 1%, 3%, and 5% into sodium alginate films significantly increased DPPH and

ABTS activities, with the highest values reaching 66.47% and 70.12%, respectively.

Lily polysaccharide (LP), which is the predominant and most active component in lily bulbs, exhibits a range of beneficial properties, including antioxidant, hypoglycemic, immunoregulatory, and anti-tumor activities ([Cui et al., 2022](#)). Additionally, it has been proven that LP possesses antibacterial effects against several bacteria, such as *Bacillus cereus*, *Pseudomonas putida*, *Micrococcus luteus*, and *Klebsiella pneumoniae*. Its antioxidant capacity is comparable to that of VC in scavenging ABTS, DPPH, hydroxyl, and superoxide anion free radicals, and the antioxidant activity increases with increasing concentration ([Hui et al., 2019](#)). Due to the unsatisfactory film-forming properties of lily polysaccharide (LP)-based edible films, Cui reported a method to improve the tensile properties and the barrier properties to water and oxygen by combining sodium alginate (SA) and cold plasma (CP) treatment to prepare CP-SA/LP films ([Cui et al., 2022](#)). SA incorporation and CP treatment significantly increased the membrane tensile strength (from 13.73 MPa to 15.82 MPa) ($p < 0.05$). As the amount of SA added increased, elongation at break showed a significant decline ($p < 0.05$) from 21.22% to 2.4%, indicating the enhancement of stiffness and the reduction of flexibility with the addition of SA. The water vapor permeability of the film was effectively altered after SA addition and reached the lowest point (15.64 meq/kg) when the ratio of SA: LP was 1:3. The resulting CP-SA/LP films showed good antioxidant and antibacterial activity in the preservation of chicken breast. On the seventh storage day, CP-SA/LP-wrapped samples showed markedly reduced ($p < 0.05$) counts of *S. aureus* and *E. coli* O157:H7 at all time points, with eradication rates achieving 95.64% and 90.37%, respectively. The TBARS value in the control sample progressively increased over the storage period, reaching 0.173 mg MDA/kg by day 7. In contrast, the value decreased to 0.114 mg MDA/kg after seven days of storage in the CP-SA/LP-wrapped samples.

5.4.2 Proteins

Proteins are considered one of the most important biopolymers due to their diverse spatial structure and active groups, which enable them to form strong bonds through various types of interactions and possess various functional properties. The primary sources of raw materials for protein-based active packaging are derived from animals and plants. For proteins with film-forming properties, the most frequently utilized proteins for food packaging include wheat gluten (WG), whey, soybean, fish gelatin, and corn zein ([Hadidi et al., 2022](#); [Schmid & Müller, 2019](#)). For proteins that do not possess film-forming ability but retain active function, antimicrobial agents such as peptides, lysozyme, lactoperoxidase, and oxygen-scavenging agents such as glucose oxidase, catalase, and glutathione peroxidase have been commonly used in the preparation of active packaging. When proteins come into contact with neighboring molecules at the interface, they can create a cohesive and viscoelastic film. The physical properties of these films heavily depend on molecular characteristics such as molecular weight, conformation, charge, and flexibility. The mechanical characteristics of the films are significantly influenced by factors such as the extent of elongation, sequences of amino acids, and the overall distribution and cumulative effects of interactions among protein chains.

- **WG**

WG is a plant protein responsible for dough formation in wheat flour and exhibits favorable film-forming properties under various industrial processes. To achieve WG film with functional activity to keep the packaged food fresh, in the latest study, Chen et al. presented a cost-effective alternative method for producing packaging films utilizing naturally derived materials, including wheat gluten and lignocellulose nanofibers (LCNF-WG), which possess antimicrobial, UV blocking, water-resistant, and degradable properties with barrier capabilities against oxygen and water vapor to $15.9 \text{ cm}^3 \mu\text{m m}^{-2} \text{ day}^{-1} \text{ kPa}^{-1}$ and $10.3 \text{ g mm}^{-1} \text{ m}^{-2} \text{ day}^{-1}$, respectively ([Yian Chen et al., 2022](#)). The water vapor permeability rates (WVTR) of WG films were found to be 2–5 orders of magnitude higher than those of typical polymeric

packaging films. Rovera et al. utilized a sol-gel chemistry approach to incorporate WG into a silica network in order to address the moisture sensitivity of this protein ([Rovera et al., 2020](#)). The deposition of the WG/silica hybrid coatings resulted in approximately a four-fold reduction in WVTR at 23°C under 65% relative humidity when using the specific cellulose as substrate in this study.

- **Antimicrobial Peptides**

Antimicrobial peptides (AMPs) are naturally occurring, immune-related small molecule polypeptides. They are present in nearly all forms of life, ranging from bacteria and plants to invertebrates and vertebrates, including mammals. These peptides are regarded as promising candidates for novel antimicrobial agents due to their inhibitory effects on a wide range of pathogens, including multidrug-resistant bacteria ([Malik et al., 2016](#)). The mechanism of most AMPs' antimicrobial action is mainly due to positively charged antimicrobial peptides electrostatically interacting with negatively charged phospholipid groups on the bacterial membrane, thus altering the integrity of the membrane, increasing membrane permeability, or forming pores on the membrane surface. However, it was found that the antimicrobial peptide Bac5 kills *E. coli* cells through a different mechanism by inhibiting protein synthesis via binding to ribosomes in the cytoplasm, thereby preventing bacterial growth and reproduction ([Mardirossian et al., 2018](#)).

Previous research has demonstrated the successful integration of AMPs, such as HsAFP1, DmAMP1, Rs-ARF2, daptomycin, and heliomicin, into active packaging and highlighted their crucial contribution to food preservation. Nisin, an antimicrobial peptide composed of 34 amino acids synthesized by *Lactococcus lactis* subsp. *lactis*, is one of the most widely utilized food preservatives for over six decades in the food industry ([Khan & Oh, 2016](#)). The United States Food and Drug Administration considers nisin to be “Generally Recognized as Safe” (GRAS), and numerous other countries also permit its use as an additive for preserving food ([Khan & Oh, 2016](#);

Innovative Food Science & Emerging Technologies). So far, nine natural nisin variants (types A, Z, F, Q, U, U2, P, H, O) have been identified ([J. Wu et al., 2023](#)). Besides traditional strategies such as refrigerated storage conditions, vacuum packing, the addition of preservatives, and modified atmosphere packaging to extend the shelf life of food products, the development of antimicrobial active packaging containing nisin has emerged as an effective solution for the preservation of meat, cold-smoked salmon, Minas frescal cheese, and fruits. When beef burgers were packed in nisin-activated packaging during storage, it was found that the active packaging significantly slowed the proliferation of total viable bacteria and lactic acid bacteria. Through culture-independent analysis using pyrosequencing of RNA directly extracted from meat, it was found that the predominant operational taxonomic units (OTUs) common to both control and treated samples included *Photobacterium phosphoreum*, *Lactococcus piscium*, *Lactobacillus sakei*, and *Leuconostoc carnosum* ([Ferrocino et al., 2016](#)).

- **Oxygen-Consuming Enzymes**

The integration of oxygen-consuming enzymes into or onto the food-contact surface of polymer packaging materials has been investigated as an alternative oxygen-scavenging method for preserving liquid foods. The most commonly used ones include glucose oxidase, catalase, and glutathione peroxidase. Glucose oxidase can highly specifically oxidize glucose into gluconic acid and hydrogen peroxide under aerobic conditions. During this process, oxygen in the packaging is consumed, thus creating a low-oxygen microenvironment that inhibits the growth and reproduction of aerobic microorganisms and oxidation-induced deterioration, thereby achieving the purpose of preservation. How to maintain sufficient retention of enzyme activity when exposed to packaged food and how to introduce enzymes at high throughput onto a material surface are the two primary challenges hindering the commercialization of enzymatically active packaging technologies. To address these problems, Wong et al. developed an

enzymatic oxygen scavenging system in which hydrophobic modification of glucose oxidase was achieved by using charged surfactants to interact with the free amine groups present on the enzyme's surface ([Wong et al., 2017](#)). The hydrophobic glucose oxidase was then blended with ethylene vinyl acetate. This formula shows promise as a commercially viable coating material for immobilizing enzymes. The coatings successfully decreased the headspace oxygen by 2% in a sealed vial system containing 50 vol% citrate buffer at pH 3.5.

5.4.3 Lipids

Both proteins and polysaccharides exhibit outstanding film-forming ability, but their high hydrophilicity often leads to low gas and water vapor barrier properties. The favorable characteristics of certain lipids, such as their compatibility with other substances that form films and their ability to block water vapor and gases effectively, make them highly desirable as material modifiers in the manufacturing of food-grade films and coatings. By incorporating hydrophobic lipids into protein or polysaccharide-based films, it becomes feasible to combine the respective merits of these components. Fatty acids, waxes, neutral lipids, and resins frequently utilize lipid compounds in the production of edible films and coatings ([Yousuf et al., 2022](#)). Extensive studies have proved that some lipids possess broad-spectrum antimicrobial activity ([Casillas-Vargas et al., 2021](#); [Nurul Syahida et al., 2020](#); [Rodrigues et al., 2014](#)). The chain lengths, degrees of unsaturation, and concentrations of lipids influence the film properties and the final corresponding preservation effects ([Sun et al., 2021](#); [Yousuf et al., 2022](#)).

- **Wax**

The effectiveness of saturated fatty acids in reducing WVTR of whey protein isolate films was found to be higher compared to unsaturated fatty acids ([Fernández et al., 2007](#)). The addition of various types of natural waxes like candelilla wax ([Kowalczyk & Baraniak, 2014](#)),

beeswax ([Navarro-Tarazaga et al., 2011](#)), and carnauba wax to biopolymer films has been found to result in decreased water vapor permeability and solubility ([Rodrigues et al., 2014](#)). Kowalczyk et al. investigated the impact of varying concentrations of candelilla wax (CnW) on the physicochemical and morphological properties of edible films composed of different biopolymers: carboxymethyl cellulose (CMC), oxidized potato starch (OPS), soy protein isolate (SPI), and gelatin (GEL). CnW was incorporated into the film-forming solutions at concentrations of 0, 0.5, 1.0, 1.5, and 2.0% (w/w). The addition of CnW significantly reduced the water vapor permeability of the films by 11.1–41.7%, compared to the control samples. Syahida et al. found that the incorporation of different concentrations of carnauba wax (0, 15%, 30%, 45%, 60%) in fish gelatin films led to improvements in the mechanical and water resistance characteristics of the obtained films ([Nurul Syahida et al., 2020](#)). The results showed that with the increase of carnauba wax concentration from 0% to 60%, the thickness of the film increased from 70.63 to 120.33 μm , and the light transmission of the film decreased significantly in the visible range of 400–800 nm. Compared with films without carnauba wax, the addition of 15% carnauba was the optimal concentration to significantly increase the mechanical properties and water resistance of the films. Palm wax is primarily made up of saturated fatty acids with long carbon chains, mainly palmitic acid (C16:0) and oleic acid (C18:1), which contribute to its exceptional water resistance. With the incorporation of 15% palm wax in the fish gelatin film, the water vapor transport was in the range of $1.02 \times 10^{-10} \sim 1.25 \times 10^{-10} \text{ gm}^{-1}\text{s}^{-1} \text{ Pa}^{-1}$. When a higher concentration of palm wax was added, the tensile strength of the gelatin film significantly ($p < 0.05$) increased but tended to decrease. Unlike synthetic alternatives that can be costly and derived from non-renewable sources, natural waxes sourced from insects or plants offer a more sustainable option but may face limitations in availability and higher prices ([Gunawan et al., 2005](#)).

- **Fatty Acid**

The degree of unsaturation and the chain length are crucial characteristics affecting this activity. Numerous microbiological investigations have revealed that unsaturated fatty acids with medium (8–12 carbon atoms) to long chains (>12 carbon atoms) generally exhibit higher effectiveness against both gram-positive and gram-negative bacteria, with gram-positive bacteria being more susceptible ([Solano et al., 2020](#)). Through a comprehensive analysis of saturated fatty acids with hydrocarbon chains ranging from 6 to 18 carbons, it was found that lauric acid (LA), which features a 12-carbon chain, demonstrates the strongest inhibitory effect on the growth of gram-positive bacteria and also exhibits antimicrobial properties against a range of microorganisms, including gram-positive bacteria, viruses, and various phytopathogenic fungi like *Rhizoctonia solani* and *Pythium ultimum*. The 1-monoglyceride derivative of LA, known as glyceryl monolaurate (GML), exhibited even higher efficacy against *S. aureus*, as evidenced by its lower minimum inhibitory concentration (MIC) compared to LA. Both LA and GML are generally recognized as safe by the U.S. Food and Drug Administration. Hence, these compounds have been extensively investigated for their potential in antimicrobial packaging development. Moreover, capric acid and its monoglyceride derivative, monocaprin, both possessing 10-carbon saturated hydrocarbon chains, along with three C18 unsaturated fatty acids, including petroselinic acid, elaidic acid, and oleic acid, also exhibit significant antibacterial activity ([J.-H. Lee et al., 2022](#); [Yoon et al., 2018](#)). In a recent study, Solano et al. developed an LDPE active polymeric packaging using LA as an antifungal agent for preserving yellow tree tomatoes. The incorporation of LA led to a significant decrease in water vapor permeability but an increase in the tensile strength of the film, while its thermal properties remained unchanged. Yellow tree tomatoes inoculated with *Colletotrichum tamarilloi* were packaged in this film and stored at room temperature (24°C) with a relative humidity of 50% for a period of 21 days. The findings indicate that incorporating LA at a concentration of 3.5% yielded the most

effective outcomes by preventing fungal growth for three weeks, thereby extending the shelf life by an additional two weeks compared to the pure LDPE control ([Solano et al., 2020](#)).

5.5 BIOMATERIALS DERIVED FROM CHEMICAL SYNTHESIS

[Figure 5.3](#) illustrates the quantity of biopolymers manufactured in 2024. They are mainly divided into three groups:

1. Bio-based or partially bio-based non-biodegradable plastics, including bio-based polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET);
2. Bio-based and biodegradable plastics, including polylactic acid (PLA), polyvinyl alcohol (PVA), polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS);
3. Plastics derived from fossil resources that possess biodegradable properties, such as polybutylene adipate terephthalate (PBAT).

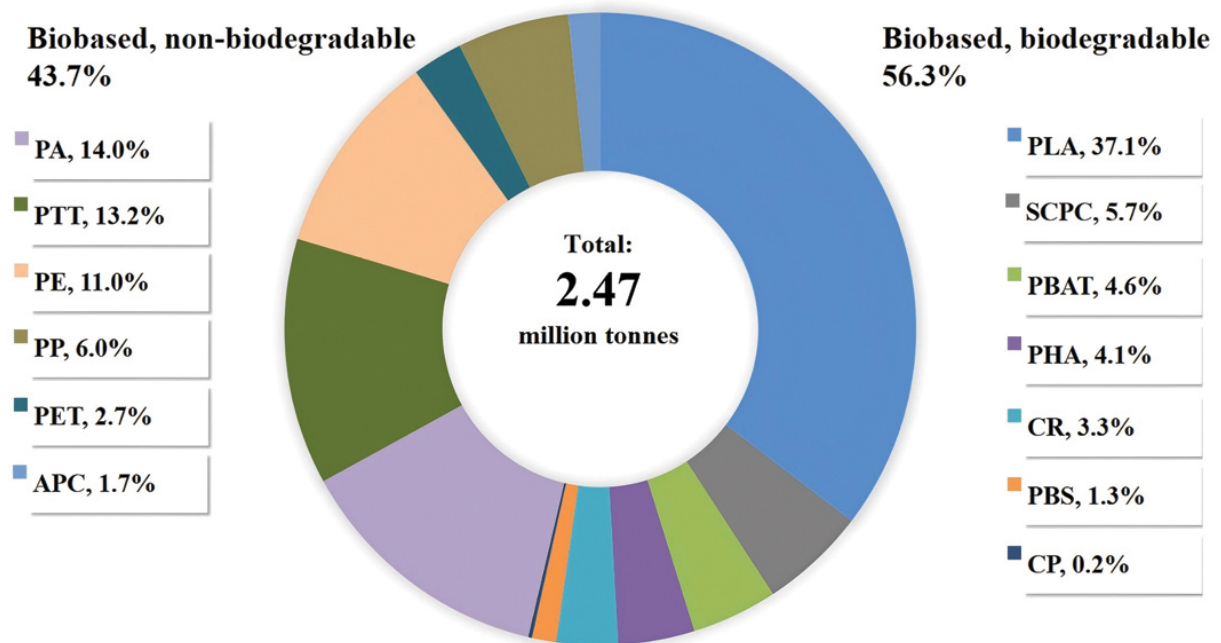


FIGURE 5.3 Global production capability of biopolymers in 2024. Data was collected from the european bipolymers organization. [↗](#)

In the field of food packaging, biomaterials derived from chemical synthesis have been commercially utilized due to their favorable characteristics, such as excellent biodegradability, compatibility, and processability. Among these bioplastics, biodegradable materials are the mainstream, accounting for as much as 56.3% of biodegradable plastics. PLA has become the largest bio-based polymer production, accounting for 42.8% of the global production of biopolymers. Bio-based non-biodegradable polymers, including polyamide (PA), poly (trimethylene terephthalate) (PTT), and PE, are the most commonly used non-biodegradable plastics, accounting for 43.7% of total biopolymer production.

- **PLA**

PLA is one of the commercially available bio-based thermoplastic polyesters and is produced through the polymerization of lactic acid derived from natural sources such as corn and sugarcane ([Choi et al., 2024](#)). It is derived from renewable and biodegradable resources and

can undergo simple hydrolysis to break down into water and carbon dioxide. This characteristic makes PLA a renewable, biodegradable, biocompatible material with excellent mechanical properties. It has become one of the most extensively studied biodegradable polymers for environmentally sustainable packaging materials, showing great potential as an alternative to petroleum-derived polymers. However, due to its poor barrier properties against oxygen and water vapor, PLA often needs to be used in combination with other materials or adjust its L-lactic acid and D-lactic acid ratio to enhance the crystallinity of PLA film and improve its barrier performance ([Yuanyuan Chen et al., 2016](#)). Blending PLA with PCL, PHB, poly (butylene succinate adipate) (PBSA), and cocoa bean shell has been shown to modify the final properties, such as mechanical strength, thermal characteristics, and biodegradation behavior. For example, Papadopoulou et al. found that incorporating 75 wt % cocoa bean shell enhanced Young's modulus by 80% and decreased the oxygen permeability to as low as $10 \text{ mL} \cdot \mu\text{m} \cdot \text{m}^{-2} \cdot 2\text{ut}^{-1} \cdot 1\text{ut}^{-1}$ at 50 wt % cocoa bean shell compared with neat PLA film, endowing the composites with antioxidant properties ([Papadopoulou et al., 2019](#)). Fiore et al. reported a new antioxidant PLA-based film whose surface was coated with a chitosan/sodium caseinate blend enriched with rosemary essential oil (at concentrations of 1% and 2%). The presence of the coating reduced the water vapor transmission rate to the lowest value ($1.23 \pm 0.03 \times 10^{-4} \text{ g m}^{-2} \text{ s}^{-1}$) with 2% rosemary essential oil. Fresh minced chicken meat wrapped in the active film maintained stable malondialdehyde (MDA) levels and color for up to 14 days (4 °C, film-to-meat ratio was 4.8 mg/g). Additionally, these samples showed a decrease in heptanal and ethanol concentrations by 72% and 90%, respectively, compared to those packed with the control film ([Fiore et al., 2021](#)). Active packaging based on PLA and chitosan-caseinate enriched rosemary essential oil coating for fresh minced chicken breast application (*Food Packaging and Shelf Life*, 29, 100708). The improvement in polymer properties is influenced not only by the type and concentration of essential oils but

also by the compatibility between the polymer matrix and the essential oils. The incorporation of essential oils at 9 wt% loading into the polymer matrix resulted in a reduction in the glass transition temperature ([Yuyue Qin et al., 2017](#)). Traditional techniques like solvent casting, melt blending, or compression molding have been employed to incorporate active agents into various polymer films. However, these methods all encounter specific limitations, including the evaporation and thermal degradation of the active compounds. Lukic et al. reported an approach to decrease the loss of active ingredients by loading thymol and carvacrol into PLA/PCL blended polymer-carriers using supercritical CO₂ as an impregnation medium at 40°C and 10 MPa for 5 hours, achieving loadings of 27.53% and 21.18%, respectively ([Lukic et al., 2020](#)).

- **PBAT**

PBAT is a biodegradable aliphatic-aromatic polyester that has been commercially produced through the polycondensation of 1, 4-butanediol, terephthalic acid, and adipic acid. The synthesis of PBAT involves several steps, including esterification, condensation, and melt polymerization with the assistance of titanium organometallic compounds as catalysts ([Roy et al., 2024](#)). Compared to other biopolymers, PBAT films possess a high degree of flexibility that makes them highly suitable for applications in active food packaging ([Jariyasakoolroj et al., 2020](#)). Currently, most commercially available biodegradable packaging is composed of PLA and PBAT. However, PLA/PBAT films exhibit relatively low mechanical characteristics as well as inferior barrier properties compared to traditional plastics, resulting from their incompatibility and immiscibility, which restricts their wide application under mechanical stress ([Papadopoulou et al., 2019](#)).

In recent years, researchers have investigated the incorporation of functional agents to endow films with preservation functions and to enhance the physical properties of PBAT/PLA films. For example, Som et al. chose glucono-delta-lactone as a multifunctional additive to

prepare PBAT/TPS blended films, where glucono-delta-lactone acted both as an innovative compatibilizer and as an antimicrobial agent for packaging applications ([Som & Harnkarnsujarit, 2024](#)). PBAT/PLA films incorporating ginger oil and lime peel oil showed promise for seafood packaging ([Laorenza & Harnkarnsujarit, 2023](#)). In addition to PBAT/PLA-based film, thermoplastic starch/PBAT films could also compensate for the performance deficiencies of neat PBAT film. Sodium nitrite, as a food additive, plays a crucial role in maintaining the appealing pink color of meat products and preventing microbial proliferation in red meat products. Due to consumer concerns about the health hazards caused by the use of nitrates, Katekhong et al. prepared thermoplastic starch/PBAT films incorporating nitrates via blown-film extrusion ([Katekhong et al., 2022](#)). This functional, active packaging offers an alternative method to reduce the need for direct addition of food additives to meat. The addition of 5% nitrates significantly improved the oxygen barrier properties. For the 40% PBAT/60% TPS and 30% PBAT/70% TPS films, the corresponding oxygen permeability values were 4.5 and 1.2 $\text{cm}^3\cdot\text{mm}/\text{m}^2\cdot\text{day}\cdot\text{atm}$, respectively. Films containing nitrates led to lower residual nitrite levels and significantly improved the redness of the packaged meat over 12 days of storage.

- **PVA**

PVA is generated by polymerizing vinyl acetate to form polyvinyl acetate, which is then converted into polyvinyl alcohol through an alcoholysis reaction. The characteristics of polyvinyl alcohol are primarily influenced by its molecular weight and degree of hydrolysis. PVA typically exhibits a molecular weight ranging from 20,000 to 400,000 and a degree of hydrolysis varying between 80% and 99%, depending on the length of vinyl acetate used during production. The potential preserving application of PVA films in active packaging for meat products, fresh-cut apples, strawberries, and milk has been widely documented ([Dong et al., 2016](#); [Huie et al., 2023](#); [B. Liu et al., 2017](#); [Qu et al., 2023](#)). However, the oxygen transmittance of PVA-

based film is significantly influenced by the relative humidity of the environment. When the relative humidity exceeds 75%, there is an exponential increase in the oxygen permeability of PVA. To reduce the water sensitivity of PVA and enhance its suitability for high oxygen barrier packaging, Zhu et al. developed a composite coating film by chemically crosslinking PVA with melamine-formaldehyde resin (MF) ([Zhu et al., 2021](#)). The C-O-C bond and strong interfacial interaction between MF and PVA facilitate enhanced crosslinking, thereby improving the thermal stability, mechanical properties, and barrier performance of PVA/MF film. Even at 75% relative humidity, the oxygen permeability of the PVA/MF composite film was kept at approximately $1.0 \text{ cm}^3 \text{ m}^{-2} \text{ d}^{-1}$. A range of functional nanofillers, including metal nanoparticles, metal oxides, clay, and graphene, have been utilized to develop PVA/ST-based nanocomposites to widen the functionality of PVA-based films. These nanocomposites exhibit enhanced physicochemical properties and specialized functionalities, such as UV protection, photocatalytic activity, antibacterial effects, and antioxidant capabilities. For example, Yu et al. discovered that integrating bioinspired polydopamine nanoparticles not only enhanced the compatibility and physical characteristics of the films but also imparted exceptional UV/HEBL blocking, thermal insulation, and antioxidant properties to the PVA/ST composite film. Consequently, these high-performance, multifunctional nanocomposite films can safeguard food quality from photothermal oxidative degradation and prolong food shelf life ([J. Yu et al., 2022](#)).

5.6 BIOMATERIALS DERIVED FROM MICROORGANISM SYNTHESIS

Microorganisms are capable of synthesizing intracellular, structural, and extracellular biopolymers to meet their functional needs and ensure

survival. For example, when pathogenic bacteria colonize the host's surface, they produce various types of exopolysaccharides (such as pullulan, alginate, cellulose, and hyaluronate) that play a crucial role in biofilm formation. A previous study found that *Escherichia coli* generates phosphoethanolamine cellulose to strengthen proteinaceous curli fibers by creating cement-like formations. These fibers enable strong intercellular connections within complex biofilms and provide stable binding against high shear forces. Biomacromolecular exopolysaccharides, such as alginate, cellulose, and hyaluronate, are recognized as crucial virulence factors in the formation of the biofilm matrix. While these biopolymers exhibit important virulence attributes when synthesized by pathogenic bacteria, they become essential components of food or biomaterials if produced by non-pathogenic bacteria. These synthesized biopolymers, such as pullulan, cellulose, kefiran, levan, gellan, xanthan, dextran, and polyhydroxyalkanoates (PHAs), possess excellent film-forming properties, could potentially serve as ideal alternatives to conventional plastics.

- **Pullulan**

Pullulan, having the molecular formula $(C_6H_{10}O_5)_n$, is an extracellular, linear, hydrophilic exopolysaccharide ([Vijayendra & Shamala, 2014](#)). In 1938, pullulan was first reported by Bauer, who extracted it from the fermentation broth of *Aureobasidium pullulans* ([Cheng et al., 2011](#)). The production of pullulan began in 1976 by Hayashibara Co., Ltd (Okayama, Japan), and its introduction to the market occurred in 1982 through the availability of films based on this biopolymer ([X. Chen et al., 2017](#); [Farris et al., 2014](#)). The structure of pullulan consists of repeating units of maltotriose connected by α -1, 6-glucosidic bonds. This polysaccharide is produced by two types of fungi, namely *Aureobasidium pullulans* and *Eurotium chevalieri* ([Barcelos et al., 2020](#); [Vijayendra & Shamala, 2014](#)). Pullulan is extensively employed in the production of active food packaging owing to its remarkable film-forming ability and water solubility.

However, one of the great challenges for the widespread use of this microorganism-synthesis polymer is its high cost.

- **Polyamide**

Several bacteria, including *Bacillus licheniformis*, *Bacillus megaterium*, and various cyanobacteria, have been explored as potential candidates for synthesizing polyamide materials. Polyamides possess high charges and can exhibit either polyanionic characteristics (such as γ -PGA) or polycationic properties (for instance, ϵ -PL). Among them, ϵ -polylysine (ϵ -PL), a byproduct of microbial metabolism, has gained significant popularity in the field of food preservation due to its remarkable safety and wide-ranging antimicrobial properties against both gram-positive and gram-negative bacteria, molds, and yeasts ([Alirezalu et al., 2021](#); [Zheng et al., 2023](#)). ϵ -PL serves as a valuable nutritional antimicrobial agent since it can be broken down into lysine—an essential amino acid for human health—without posing any toxic effects on human health. As a preservative, ϵ -polylysine has obtained Generally Recognized as Safe (GRAS) certification from the U.S. Food and Drug Administration ([Yang et al., 2024](#); [Zheng et al., 2023](#)). However, incorporating ϵ -polylysine directly into food products presents challenges in terms of stability and long-lasting preservation effectiveness. To overcome this obstacle, researchers have investigated the encapsulation of ϵ -polylysine in biopolymer-based films and coatings to enhance their stability. Additionally, the utilization of ϵ -polylysine as a cross-linking agent and antimicrobial agent has been explored to strengthen the preservation capabilities of these films and coatings. Numerous recent studies have demonstrated significant improvements achieved by incorporating ϵ -polylysine into various biopolymer-based films and coatings, including materials such as chitosan, starch, alginate, gelatin, polyvinyl alcohol, levan/pullulan/chitosan blend, and tannic acid. Moreover, these functionalized biopolymer-based films and edible coatings show exceptional potential for preserving a wide range of fresh foods such as meat, fruits and vegetables, fish, and seafood.

5.7 PROCESS FOR PREPARING ACTIVE PACKAGING

Currently, the processes for preparing active packaging materials using biopolymer matrices primarily include the solvent casting technique, melt extrusion, and coating via layer-by-layer assembly. The casting process involves dissolving the polymer matrix and active agents in a specific solvent, followed by casting the resulting mixture onto a mold or glass plate. After complete evaporation of the solvent, the desired active film was fabricated. The process is only suitable for pilot tests since it is difficult to control the uniformity of materials. For the melt extrusion process, the master batch is melted in a heated barrel and subjected to rotational force exerted by a screw. Subsequently, the molten and compressed master batch is directed through a shaping die to form a thin film, followed by cooling and removal using nip rolls. This process is the main way of producing films on a large scale. However, it is worth noting that this process leads to activity deterioration of most active ingredients due to their chemical instability under the conditions of high temperature, high pressure, and rotational shearing encountered during this process ([Del Nobile et al., 2009](#)). The coating technique offers a straightforward and convenient approach for the fabrication of active packaging films by casting a solution containing active extract onto the surface of commercial film through physical and chemical immobilization ([Yong & Liu, 2021](#)). Compared to other preparation methods, coating enables the even dispersion of active compounds within the inner layer of the packaging without undergoing heat or mechanical action, thereby minimizing activity loss. Especially, layer by layer (LBL) is a prevalent way for coating, which involves the spontaneous association of layers to form a molecular aggregate or supramolecular structure with stable architecture, exhibiting specific functions through the method of alternating deposition and weak intermolecular interactions (such as electrostatic attraction, hydrogen bonding, and coordination bonding). It

is characterized by its ease of operation and flexible application and serves as an important approach for enhancing packaging's resistance to oxygen, improving mechanical performance, and reducing microbiological growth ([Ariga et al., 2007](#); [Ganjeh et al., 2024](#)). LBL technology offers dual advantages in constructing coatings on film surfaces by integrating packaging functionality and self-assembly surface modification.

In recent years, electrospinning technology has garnered increasing attention in the development of active packaging. It is a non-thermal process that utilizes high applied voltage to induce a spinning solution or melt into fibers with diameters ranging from micrometers to nanometers. The conventional electrospinning device primarily comprises three main components: high-voltage power supply, injector/pump, and collector. As depicted in [Figure 5.4](#), as the applied voltage increases, the droplets at the tip of the injection needle gradually overcome their surface tension and transition from a spherical shape to a conical shape, forming a Taylor cone. The charged spinning liquid droplets undergo whipping and stretching during this process, resulting in fiber formation. Depending on the desired function and physical characteristics, multifunctional composite materials can be produced using diverse spinnable materials. Due to its low spinning cost, simple operation process, and non-thermal nature, electrospinning has found wide applications in biomedical engineering, renewable energy systems, sensors, wastewater treatment, air purification, and food packaging, among other fields. The prepared nanomaterials exhibit several distinctive features: (1) The fiber diameter is distributed as small as tens to hundreds of nanometers, enabling them to form a unique “spiderweb”-like structure with an exceptionally high specific surface area. This facilitates exploiting size effects of nanomaterials while significantly enhancing surface energy and reaction efficiency of active functional components. (2) The porous carrier interface promotes effective infiltration and diffusion of functional factors within food media, resulting in enhanced contact between them. (3) Numerous studies have confirmed that embedding active factors within polymer-based fiber matrices provides a protective layer for these

functional factors, which greatly improves stability of deoxygenated active ingredients.

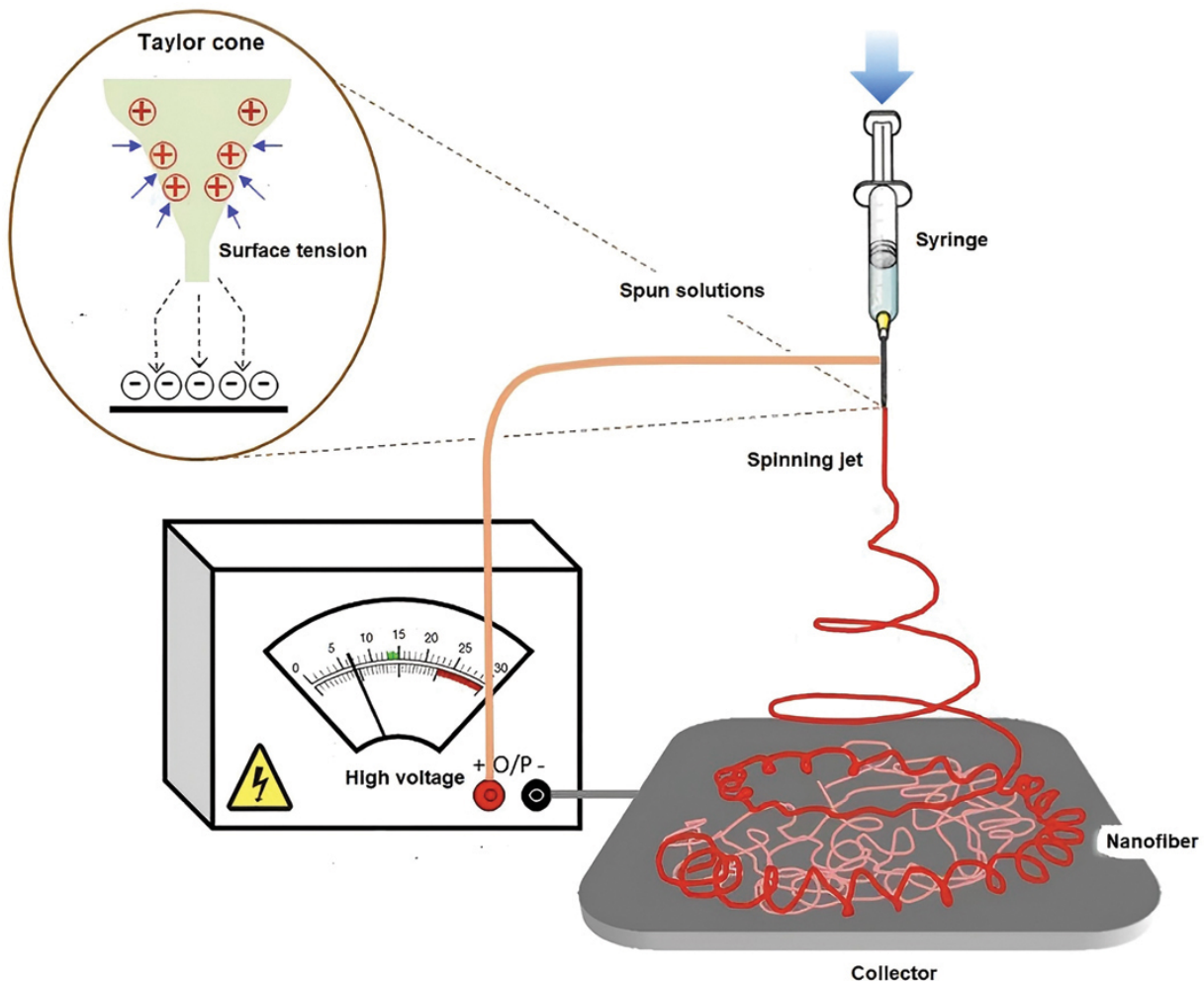


FIGURE 5.4 Diagram of the electrospinning process. [📄](#)

5.8 APPLICATION OF ACTIVE PACKAGING

As shown in [Figure 5.5](#), active packaging based on biomaterials shows great potential to extend the shelf life and maintain the quality of liquid foods, meat products, vegetables, fruits, and seafood.

5.8.1 Fruits and Vegetables

Fruits and vegetables remain living organisms after harvest, maintaining metabolism by consuming their own nutrients, which forms the unique post-harvest physiology. It is estimated that the postharvest loss of fruits and vegetables ranges from 45% to 55% due to improper storage methods, leading to serious inefficiency in resource and production utilization. Low-temperature storage, sulfur dioxide fumigation, and antimicrobial spraying have been widely applied for fruit and vegetable preservation. However, the energy consumption due to subzero refrigeration and the potential health hazards of antimicrobial residues require food technologists and engineers to seek energy-saving, safe, and low-cost preservation methods. Liu et al. combined chitosan, PLA, and multi-walled carbon nanotubes (CNTs) to prepare PLA/CNTs/chitosan nanofibers with varying chitosan content (0, 1, 3, 5, 7, 9 wt%) ([Y. Liu et al., 2019](#)). The results show that the antibacterial rates against *Escherichia coli*, *Staphylococcus aureus*, *Lactobacillus brevis*, and *Rhizopus stolonifer* reached 91.5%, 94.6%, 88.2%, and 90.9%, respectively. When the chitosan content is higher than 5 wt%, the nanocomposite fibers are able to reduce the deterioration of strawberries effectively. Strawberries treated with PLA/CNTs/chitosan fibers (20–25°C, 80% humidity, 8 days) exhibited a significantly slower decline in firmness compared to untreated strawberries. After eight days of storage, the firmness of the sample without wrapping was lower than 0.5 Newton, whereas the sample wrapped with PLA/CNTs/CS-9% showed the highest firmness with a value of around 1.5 Newton, suggesting that PLA/CNTs/CS nanofibers have potential as antimicrobial packaging materials for preserving fruits and vegetables. Two essential oils, cinnamaldehyde (CA) and thymol (THY), were co-incorporated into gelatin/zein nanofibers to develop edible food packaging in a recent report ([Wu et al., 2023](#)). This nanofiber film displayed excellent protection against ultraviolet-visible light and possessed superior antioxidant capabilities, achieving nearly complete DPPH free radical scavenging (99.9%) within 4 hours. At a concentration of 12.5 mg/mL, the nanofiber films exhibited substantial inhibitory effects on *E. coli* ATCC 25922, reducing bacterial growth by 67.5%. Additionally, they completely inhibited the growth of *S. aureus* ATCC 6538 and *Listeria*

monocytogenes ATCC 19115, with antibacterial efficiencies of 100%. As shown in [Figure 5.6](#), the freshness of the packaged strawberries was maintained for up to seven days at ambient temperature.

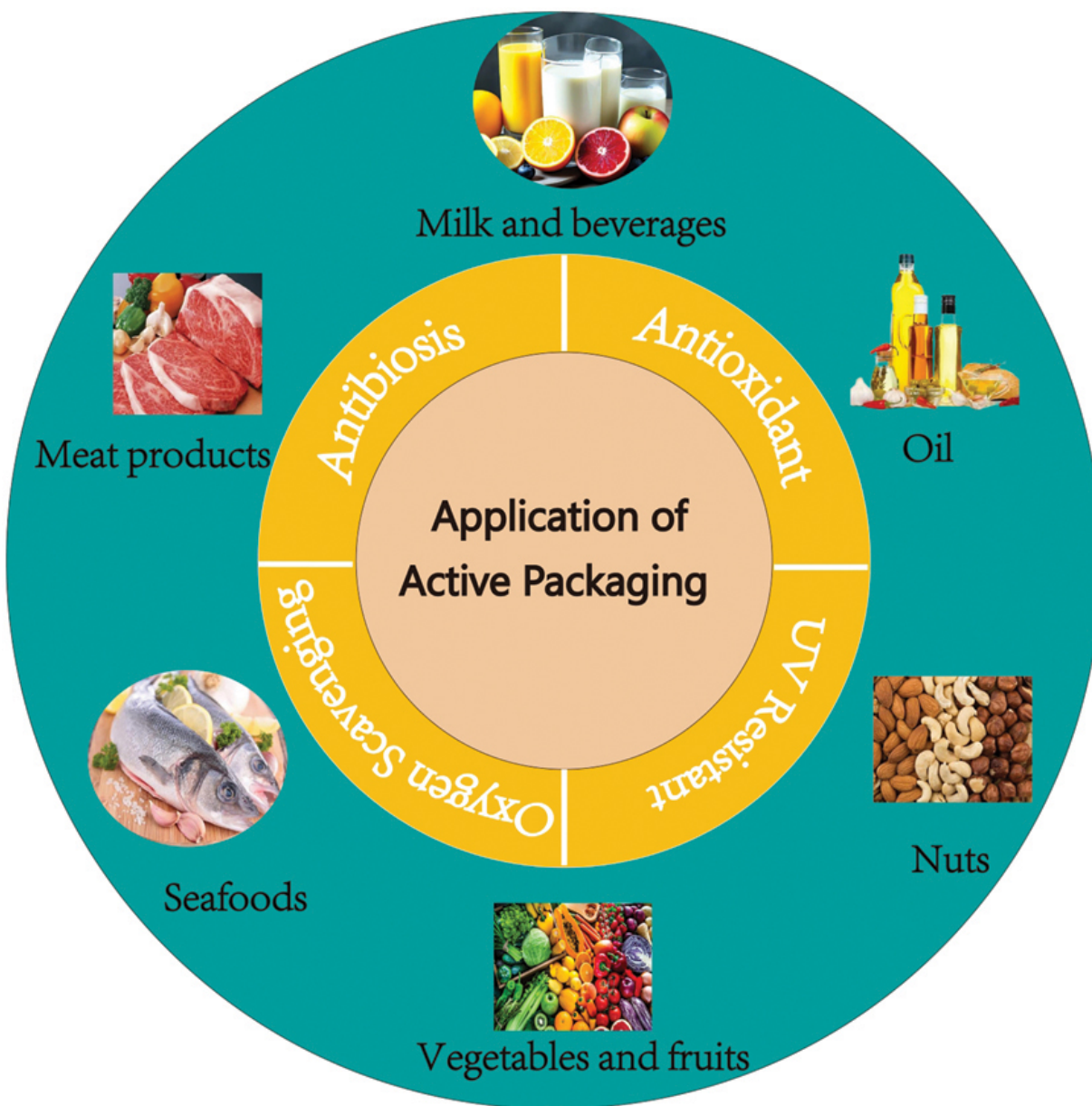


FIGURE 5.5 Application of active packaging. [↗](#)

Singha et al. reported a low-density polyethylene/gallic acid composite oxygen-scavenging film using the molten extrusion method, and its preservation effect on peeled garlic was evaluated ([Winestrand et al., 2013](#)).

The results showed that after 35 days of storage at 25 °C , the internal oxygen content of peeled garlic packaged with the composite film decreased from 20.1% to 3.2%. Additionally, compared to the control group without the composite film, the weight loss of the peeled garlic packaged with the composite film containing gallic acid was only 10% after 35 days of storage.

5.8.2 Seafood

Compared to other food products, fresh seafood is characterized by significant temperature fluctuations, long-distance transportation, and active enzymatic reactions. Temperature changes during transit can facilitate microbial growth and the formation of heat-stable toxins. Currently, chilling and refrigeration are the primary preservation methods for maintaining the freshness of seafood. However, bulk transportation of fresh fish using ice presents several challenges, including limited shelf-life extension, increased freight costs due to the weight of ice, handling difficulties, and hygiene issues from melting ice water, which can result in the loss of soluble nutrients and flavor compounds. Appropriate active packaging can significantly enhance the retention of fish quality during storage and transport. Azaza et al. developed active packaging films based on chitosan (CS) and sardinella protein isolate (SrPI), derived from blue crab and *Sardinella aurita* by-products, respectively, to investigate their impact on the quality of shrimp freshness ([Azaza et al., 2022](#)). Chitosan (2%, w/v) was mixed with varied quantities of SrPI (2%, w/v) at various volume ratios of CS-SrPI (100:0, 90:10, 80:20, 70:30, 60:40, and 50:50). The resulting composite films were labeled as CS90–10SrPI, CS80–20SrPI, CS70–30SrPI, CS60–40SrPI, and CS50–50SrPI. The films demonstrated antibacterial efficacy against all nine tested bacterial strains, with the effectiveness varying depending on both the target strain and the SrPI content. Specifically, gram-positive bacteria were generally more susceptible than gram-negative strains. Notable inhibition was observed for *Listeria monocytogenes*, *Micrococcus luteus*, and *Bacillus cereus*. However,

Staphylococcus aureus, a gram-positive bacterium, exhibited the least susceptibility among all tested samples. The preservation capacity of the composite films during shrimp storage (0, 3, 6, and 9 days at 4°C) was investigated by assessing moisture content, pH, microbiological growth, thiobarbituric acid reactive substance (TBARS), conjugated dienes (CD), and peroxide content. The moisture of the CS/SrPI film packaged pieces of shrimp was slightly increased during storage, as compared to the unpackaged pieces of shrimp (26%). For example, SH-1 showed an increase in the moisture content from 27.30%–28.78%. During nine days of cold storage, the pH values of non-packaged (SH-C) and packaged shrimp samples (SH-1, SH-2, SH-3) increased progressively from 7.42 to 7.91, 7.05 to 7.52, 6.81 to 7.13, and 6.41 to 6.89, respectively ($p < 0.05$). This pH increase can primarily be attributed to the accumulation of nitrogenous compounds resulting from microbial activity. The results showed that the higher the SrPI content in the packaging film, the lower the PV, TBARS, and CD of the packaged shrimp. The PV values of SH-1, SH-2, and SH-3 on day 9 were 0.0197, 0.0177, and 0.0157 meq/kg, respectively, and were significantly ($p < 0.05$) lower than those of unpackaged shrimp (0.0313 meq/kg lipids). After nine days of storage, the TBARS of SH-C increased to 4.36 mg MDA/kg, but the TBARS of SH-1, SH-2, and SH-3 decreased to 3.03, 2.05, and 1.84 mg MDA/kg, respectively ($p < 0.05$). Interestingly, the highest CD values were obtained in SH-C and SH-1, reaching 0.304 and 0.222 on day 9, respectively. SH-2 and SH-3 had the lowest values of 0.208 and 0.198 ($p < 0.05$), respectively. The incorporation of SrPI into the chitosan film matrix effectively mitigated pH changes, reduced lipid peroxidation, and inhibited the proliferation of total psychrophilic flora (TPF) and mesophilic flora (TMF) in packaged shrimps during refrigerated storage.

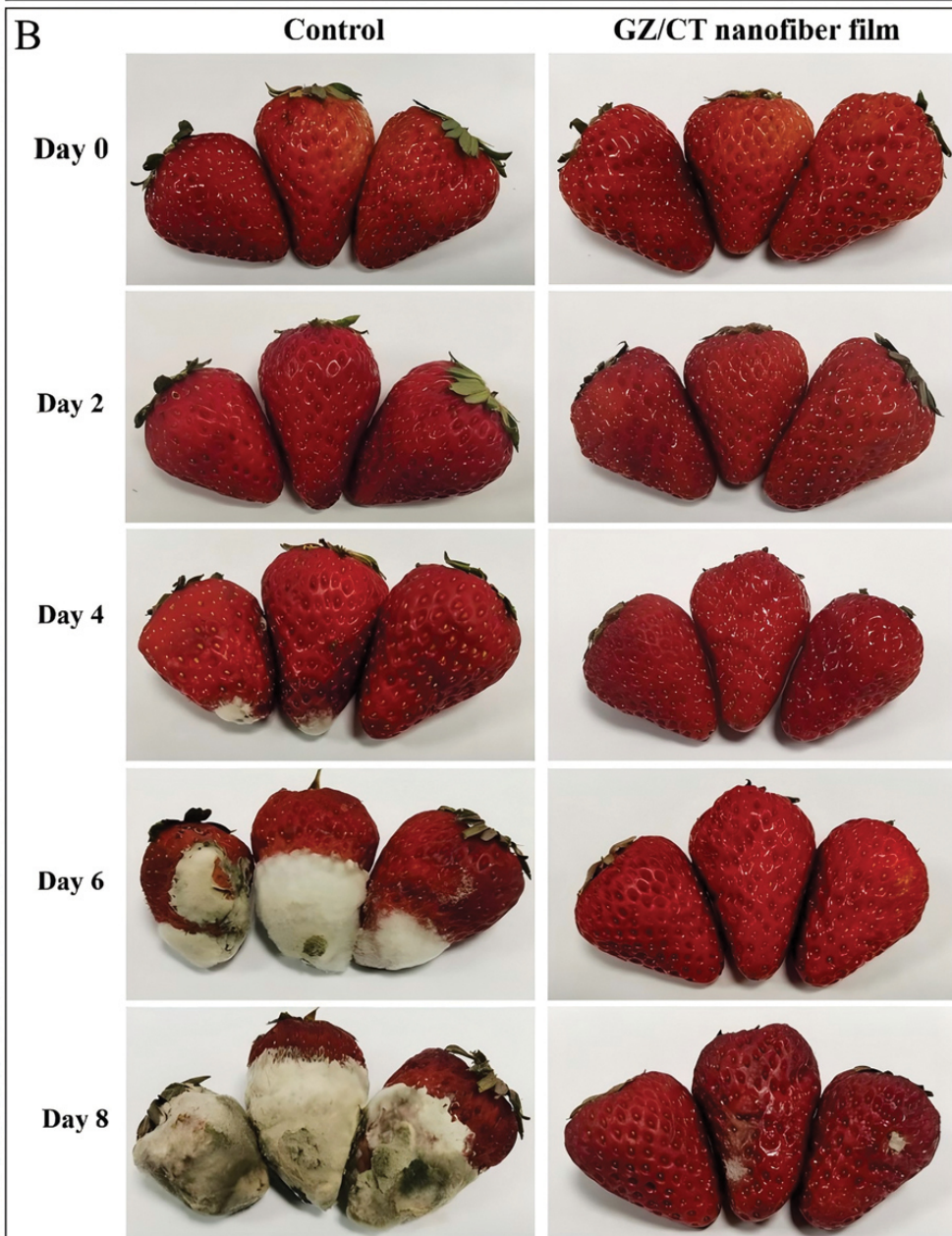
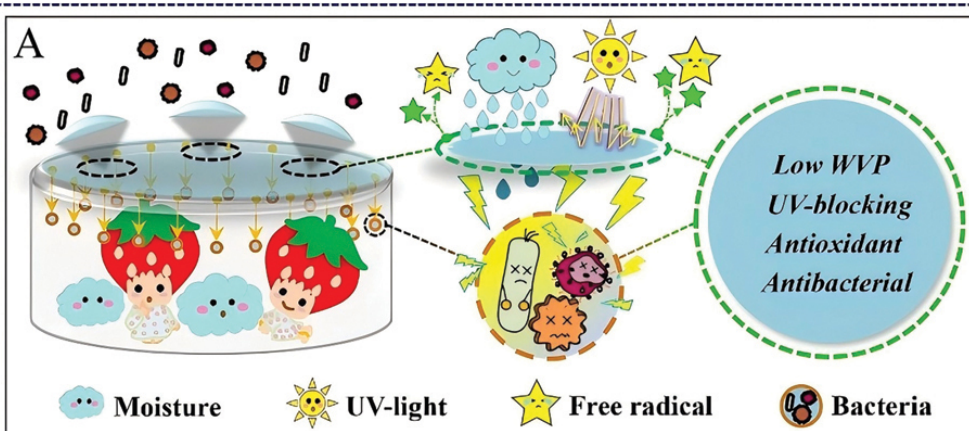
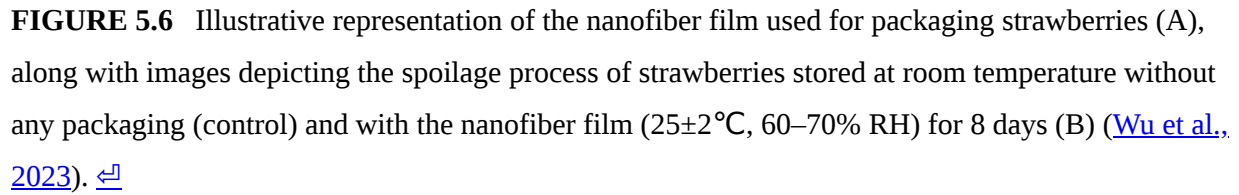


FIGURE 5.6 Illustrative representation of the nanofiber film used for packaging strawberries (A), along with images depicting the spoilage process of strawberries stored at room temperature without any packaging (control) and with the nanofiber film ($25\pm 2^{\circ}\text{C}$, 60–70% RH) for 8 days (B) ([Wu et al., 2023](#)). 

Laorenza et al. discovered that biodegradable composite films composed of PBAT and PLA, incorporating essential oils (carvacrol, citral, and α -terpineol at concentrations of 3% and 6%), effectively mitigated quality degradation in Pacific white shrimp ([Laorenza & Harnkarnsujarit, 2021](#)). This mitigation included suppressing microbial proliferation, lipid oxidation, and textural changes. Notably, the release of citral and carvacrol from the packaging played a crucial role in maintaining protein structure stability within muscle tissues, thereby reducing drip loss and preserving the adhesion between the cephalothorax and abdomen. Furthermore, all films containing essential oils successfully prevented melanosis. Kanatt et al. developed a composite active and intelligent food packaging film by incorporating Amaranthus leaf extract (ALE) into a blend of polyvinyl alcohol (PVA) and gelatin ([Kanatt, 2020](#)). The study on the practical application of this film for fish storage revealed that after three days of storage, fish packed in conventional films exhibited 5.22 log CFU/g of *S. aureus* and 4.28 log CFU/g of *fecal coliforms*. In contrast, fish stored in the active films showed significantly lower microbial counts of 3.38 log CFU/g for *S. aureus* and 3.91 log CFU/g for *fecal coliforms* even after 12 days of storage. Additionally, the active films effectively minimized oxidative rancidity and maintained freshness of the products.

5.8.3 Nut

In recent years, nuts and nut-derived products, once considered microbiologically safe, have increasingly been found to harbor foodborne pathogens such as *Salmonella* spp., *Escherichia coli* O157:H7, and *Listeria monocytogenes* ([Acuff et al., 2020](#); [McDaniel & Jadeja, 2021](#)). Certain nuts are particularly susceptible to contamination by toxigenic molds, leading to

the formation of secondary metabolites known as mycotoxins. These mycotoxins have been classified as Group 1 carcinogens by the International Agency for Research on Cancer, posing a significant risk to human health and safety through consumption. Traditional methods to ensure the quality and safety of nut products, such as the application of fungicides, chemical compounds, or thermal treatments, have been widely used. However, these methods can introduce health hazards from chemical residues and cause quality degradation due to heat treatment, necessitating the exploration of alternative approaches. Active packaging using biopolymers has shown potential in reducing fungal growth, aflatoxin production, and providing antioxidant effects for both fresh in-hull nuts and processed nuts. The study investigating the impact of active packaging containing potato starch, nano zinc oxide (1%, 3%, and 5% w/w), and fennel (*Foeniculum vulgare* Miller) essential oil (1%, 2%, and 3% w/w) on fresh pistachios during cold storage demonstrated that bionanocomposite films significantly extended the shelf life of pistachios by inhibiting the growth and spread of *A. flavus* fungi, thereby reducing aflatoxin production ([Babapour et al., 2022](#)). Furthermore, the use of active bio-nanocomposite films for packaging effectively maintained moisture levels, carbohydrate content, and fat content while minimizing weight loss during storage. Notably, the potato starch/5% Nano-ZnO/3% FEO bio-nanocomposite film was found to be the most effective in enhancing the physicochemical and sensory qualities of fresh pistachios. In recent years, the non-thermal electrospinning technique for fabricating nanofibrous films has garnered significant attention owing to its distinctive advantages. Compared with films produced via casting or extrusion, nanofibrous membranes possess an exceptionally high surface area-to-volume ratio and exhibit heightened sensitivity to environmental changes. This enables superior protection, controlled release of active molecules, and enhanced antioxidant activity. Aydogdu et al. developed hydroxypropyl methyl cellulose (HPMC)/polyethylene oxide (PEO) nanofibers encapsulating gallic acid (GA) through electrospinning ([Aydogdu et al., 2019](#)). The objective was to mask GA's unpleasant flavor, enhance its stability, and assess the feasibility

of using PEO nanofibers as active packaging materials for walnut preservation. The results demonstrated that walnuts packaged with 10% GA nanofiber exhibited significantly lower hydrogen peroxide and p-anisidine values compared to pure GA stored at 40°C for 21 days ($p < 0.05$).

5.8.4 Edible Oil

Edible oils rich in polyunsaturated fatty acids are especially prone to oxidation during processing and storage. This oxidative process results in the formation of unsaturated aldehydes and ketones, such as malondialdehyde and methyl ketone. These compounds not only compromise the sensory attributes of food (color, aroma, and taste) but also lead to the degradation of essential fatty acids, including linoleic acid and alpha-linolenic acid, along with other critical nutrients. Various antioxidant and oxygen-scavenging packaging have shown both efficacy and practicality in delaying lipid oxidation and maintaining food quality. Fass et al. employed palladium as the catalytic agent in a palladium-based oxygen scavenging film (CSP) to inhibit linseed oil oxidation through efficient oxygen scavenging ([Faas et al., 2020](#)). The results showed that after 168 days, the peroxide value of samples without CSP increased to 7.7 ± 0.2 AU/g oil, whereas CSP significantly inhibited linseed oil oxidation, keeping peroxide values below 1 AU/g oil. Vidal et al. developed carboxymethyl cellulose (CMC) films incorporating antioxidant compounds derived from green coffee oil by-products to inhibit fish oil oxidation. The formation of peroxide value (PV) and thiobarbituric acid reactive substances in fish oil samples encapsulated with C-CE and C-SE films, along with an inert headspace, was significantly lower compared to control samples stored at 40°C for 16 days. By the end of the storage period, the PV values of fish oil wrapped in C-SE and C-CE films were reduced by 80–90% relative to the control sample wrapped in aluminum foil, which had PV values of 364.2, 67.2, and 33.0 Meq O₂/kg, respectively. Additionally, the generation of secondary oxidation products was diminished by 58–80% ([Vidal et al., 2022](#)).

5.8.5 Meat

Meat is highly susceptible to spoilage due to its high water activity and has a limited shelf life when stored under improper conditions. Previous studies have shown that active packaging holds significant potential for extending the shelf life of meat products. The effectiveness of active packaging is influenced by several factors, including the properties of the carrier material (e.g., ground mustard seeds embedded in the film), storage conditions (such as relative humidity and temperature), and the composition of the packaged food (particularly its fat content). These factors collectively determine the distribution and concentration of active compounds within the packaging environment, thereby affecting bacterial growth inhibition and ultimately extending the shelf life of meat products ([Bahmid et al., 2021](#)). Bahmid et al. investigated the efficacy of allyl isothiocyanate (AITC) concentration in inhibiting bacterial growth in ground beef with varying fat contents. In low-fat ground beef, AITC concentration was lower within the product but higher in the headspace compared to medium-fat ground beef. As a result, the shelf life of low-fat ground beef was extended by 3.7 days, while that of medium-fat ground beef was prolonged by only 0.6 days. Nitrogen and phosphorus-doped carbon dots (NP-CDs), synthesized from green tea, were incorporated into chitosan/starch (Chi/St) based multifunctional nanocomposite films. The addition of NP-CDs significantly enhanced UV-light blocking efficiency, achieving 93.1% for UV-A and nearly 99.7% for UV-B while maintaining the films' water transparency and water vapor permeability. Furthermore, the incorporation of NP-CDs in Chi/St films markedly improved antioxidant properties, demonstrating 98.0% radical scavenging activity for ABTS and 71.4% for DPPH. The films also exhibited potent antibacterial effects against *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus*. When used to wrap meat and stored at 20°C, these films effectively inhibited bacterial growth (less than 2.5 Log CFU/g after 48 hours) without noticeably altering the color of the wrapped meat.

5.8.6 Milk and Beverages

Preventing rancidity and deterioration caused by microbial contamination is a cornerstone of security risk prevention and control for milk and beverages. Currently, ultra-high pressure sterilization, pasteurization, and the addition of preservatives are the preferred strategies for antibacterial preservation of liquid foods. Compared to other food categories, reports on the application of active packaging to liquid foods are relatively limited. This study evaluated the antimicrobial effects of lysozyme-activated biodegradable packaging on pear juice and rice milk. Lysozyme was immobilized within a biodegradable polylactic acid (PLA) packaging material using cold plasma technology. The results indicated that the activated packaging significantly inhibited *Listeria monocytogenes* and maintained superior and more stable color quality compared to control samples. Notably, the activated pouches demonstrated a more pronounced antimicrobial effect on samples stored at 10°C than those stored at 4°C, likely due to the accelerated release kinetics of lysozyme from the packaging material at higher storage temperatures ([Glicerina et al., 2021](#)).

Nanofibrous membranes bring new changes to food packaging, but the inherent porosity and non-directional release characteristics of membranes restrict their application in external packaging. Conversely, solid films exhibit excellent barrier properties that can effectively compensate for these limitations. In a recent study, a color-changing film composed of carboxymethyl chitosan and oxidized sodium alginate, enriched with anthocyanins from *Oxalis triangularis* subspecies papilionacea, was integrated into a gelatin/zein-linalool membrane. This composite system is designed to monitor and maintain the freshness of milk effectively. The control milk sample reached an acidity level of 18.11°T after 24 hours, whereas the sample treated with CO-OTA2@GZ-L18 only reached an acidity of 18.28°T after 48 hours. According to the Chinese National Standard (GB 5009.239–2016), milk with an acidity exceeding 18°T is deemed unsuitable for consumption. These findings suggest that the shelf life of the treated milk was extended by approximately 24 hours at 25°C.

Recent studies have developed polymer films that respond to pH changes by releasing antimicrobial molecules. Naturally occurring hydroxybenzaldehyde derivatives, such as 2-hydroxybenzaldehyde, 4-hydroxybenzaldehyde, and 3, 4-dihydroxybenzaldehyde, were selected to form Schiff bases with the primary amine groups of chitosan polymer in film form. Schiff bases are formed via a condensation reaction between aldehydes and primary amines, resulting in the formation of imine linkages ($C = N$). These imine bonds can be readily cleaved through mild acid hydrolysis. The acidic environment of carrot-orange juice triggered the release of the hydroxybenzaldehyde derivatives, which exhibited antibacterial activity against *E. coli* inoculated in untreated fresh carrot-orange juice stored at 4°C for six days at a pH of 5 ([Heras-Mozos et al., 2023](#)).

5.9 FACING PROBLEMS AND PROSPECTS

Despite extensive research carried out on active packaging technologies, their successful implementation in commercial food packaging systems remains limited, mainly derived from the following three reasons: (1) the costs of biomaterial are generally expensive than petroleum-based raw materials; (2) bio-based materials are relatively difficult to process due to complex spatial structure and functional groups; (3) their physical properties (thermal, mechanical, barrier and optical properties) are generally poor compared to conventional plastics.

Nowadays, numerous approaches have been employed to tackle these constraints, involving the utilization of diverse nanomaterials to strengthen polymeric matrices or blend with other polymers and capitalize on their respective functionalities. Despite 1D and 2D nano reinforcements having been investigated to enhance the mechanical and barrier properties, their potential safety hazard is often overlooked. Furthermore, the preparation of packaging materials still faces great challenges in terms of cost-

effectiveness, safety, and functional efficiency ([W. Zhang et al., 2023](#)). Future research will be directed toward maximizing the complementary physical characteristics and properties of raw material multi-component composites and developing functional materials that are safe to use and efficient in performance.

5.10 CONCLUSIONS

With the escalating consumer demands for fresh-keeping, high-quality, and safe products, the development of active packaging has garnered significant attention for extending the shelf life of food and ensuring its safety and quality. This chapter summarizes the current research status of various biomaterials used in active packaging, categorized by their sources. The fabrication methods of active packaging and their applications in antimicrobial, antioxidant, and oxygen-scavenging functionalities are highlighted. The challenges faced in active packaging and future prospects are discussed. The primary objective of this chapter is to serve as comprehensive information for understanding the present research landscape of biomaterials in active packaging and to provide valuable insights into the innovation of new packaging materials.

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Innovative Active Biomaterials 6 for Sustainable Development and Application in Smart Food Packaging

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6.1 INTRODUCTION

Food insecurity remains a critical global challenge, with over 800 million individuals affected by malnutrition and severe hunger ([Du et al., 2023a](#); [Upadhyay et al., 2024](#)). Simultaneously, advancements in the Internet have diversified sales strategies, leading to increased inter-regional food transportation ([Nian et al., 2022](#)). Unfortunately, nearly one-third of the world's food supply is wasted during the supply chain, mainly due to the perishability of food items, which often deteriorate soon after production or harvest ([Yin et al., 2023b](#)). Several factors that reduce the shelf life of food include microbial growth, enzymatic activity, oxidative processes, ethylene emission, and variations in temperature ([Xu et al., 2022](#); [Sultana et al., 2022](#)). To minimize food waste, it is essential to develop efficient preservation strategies. Techniques like refrigeration, the use of preservatives, the application of coatings, vacuum packaging, and active

packaging are commonly utilized for this purpose. Traditional food packaging (FP) is crucial in shielding food from environmental factors like heat, light, moisture, microbial contamination, and gases ([He et al., 2023](#)). From a marketing perspective, packaging is the first interaction point with consumers, enhancing appeal, conveying the product's purpose, and stimulating sales ([Loučánová et al., 2022](#)). Traditional packaging is versatile, accommodating items of different shapes and sizes. However, it is increasingly challenged by shifting consumer preferences, a growing variety of products, a stronger emphasis on sustainability, and the urgency to lower carbon footprints ([Hassan et al., 2023](#)). To address these issues, there is a rising interest in functional and innovative packaging solutions. The SmPc market is expected to reach “\$48.97 billion” by 2028, with a “compound annual growth rate (CAGR) of 4.49% from 2023 to 2028” ([Upadhyay et al., 2024](#)).

Recent innovations focus on enhancing the “functional properties” of biodegradable packaging. Active packaging, a novel approach, incorporates materials that release or absorb substances to protect food during storage. Meanwhile, intelligent packaging integrates indicators communicating food quality parameters such as freshness, pH, gas levels, and temperature. These features allow manufacturers, distributors, and consumers to monitor food safety and quality throughout its shelf life ([Fernández-Marín et al., 2022](#); [Rout et al., 2022](#)).

The demand for bio-based smart packaging (SmPc) in food systems is rising as industries seek alternatives to fossil-based materials. The application of such packaging is expanding across food sectors. Smart packaging (SmPc) has been widely applied in the food industry to minimize waste caused by degradation during handling, transportation, and storage. This deterioration can result from chemical reactions, enzymatic activities, and microbial spoilage ([Upadhyay et al., 2024](#)). SmPc systems act as a protective shield, safeguarding food products from various physical, chemical, and biological risks. They also play a crucial role in assessing food freshness and quality while continuously tracking time and temperature, ensuring overall product safety, and maintaining quality

standards ([Thirupathi Vasuki et al., 2023](#)). This review highlights trends in active biomaterials (ABiM) for packaging and explores the potential of bio-based SmPc solutions, including polysaccharide- and protein-based polymers and bioactive compounds. Additionally, it examines various SmPc technologies, such as “pH and gas indicators, oxygen and carbon dioxide scavengers, time-temperature indicators (TTIs), gas sensors, and freshness indicators.” The discussion addresses the challenges in applying these technologies to packaging for dairy, meat, fruits, vegetables, and seafood. Furthermore, it explores regulatory concerns, the hurdles in developing active packaging, and the possible solutions alongside emerging trends and opportunities in the field.

6.2 TRENDS IN ACTIVE BIOMATERIALS FOR FOOD PACKAGING

Researchers have explored various BiM-based FP strategies to support the transition toward a circular economy. These innovative approaches not only help extend the “shelf life of food” but also provide vital information about the packaging material, enhancing its appeal to consumers. Crucially, biomaterial-based packaging offers an eco-friendly alternative by significantly reducing the environmental burden. Such materials are typically biodegradable, helping to decrease plastic waste directed to incineration or accumulating in landfills. This approach aligns with the global emphasis on adopting industrial practices that minimize carbon footprints while addressing consumer preferences for environmentally friendly products ([Das et al., 2024](#)).

Proteins and polysaccharides represent two significant biomaterials used in bioplastic production for packaging applications ([Table 6.1](#)). ([Hadidi et al., 2022](#)). Suitable processing methods can transform proteins and polysaccharides into functional materials ideal for FP. Their natural biochemical versatility enables them to interact with and complement other

materials, making them highly adaptable for various structural and functional purposes in sustainable packaging applications ([Akhila & Badwaik, 2022](#); [Sudheer et al., 2023](#)).

Polysaccharides are widely used in FP due to their versatility and renewability. Among them, cellulose, obtained from plants or synthesized by microorganisms, is particularly prominent. While “plant-derived” and “microbial cellulose” share the same chemical structure, they differ in attributes such as purity, crystallinity, and degree of polymerization ([Shen et al., 2023b](#); [Wu et al., 2023](#)). Starch is another significant polysaccharide characterized by its crystalline nature. When heated in water, starch becomes gelatinous, altering its solubility and crystalline structure depending on water content and temperature. These changes, combined with the structural reorganization of starch molecules during cooling, influence the characteristics of “starch-based films,” which are commonly applied in FP ([García-Guzmán et al., 2022](#); [Das et al., 2024](#)).

TABLE 6.1 Recent Findings in Physicochemical and Mechanical Properties

<i>TYPES OF BIOMATERIALS</i>	<i>THICKNESS</i>	<i>OPACITY</i>	<i>WATER VAPOR PERMEABILITY</i>	<i>SWELLING DEGREE (%)</i>	<i>TENSILE STRENGTH</i>
Chitosan	0.095 mm	2.06	$1.8 \times 10^{-10} \text{ g}\cdot\text{mm}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$	110	0.01
Cellulose	0.056 mm	–	$0.20 \times 10^{-10} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	586	2.5
Starch	0.110 mm	6.83	$2.12 \times 10^{-9} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	–	25
Carrageenan	0.080 mm	–	$4.04 \times 10^{-11} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	240.34	13
Collagen	39.42 μm	–	$2.61 \times 10^{-14} \text{ g}\cdot\text{m}^{-1}\cdot\text{Pa}^{-1}\cdot\text{s}^{-1}$	–	40

<i>TYPES OF BIOMATERIALS</i>	<i>THICKNESS</i>	<i>OPACITY</i>	<i>WATER VAPOR PERMEABILITY</i>	<i>SWELLING DEGREE (%)</i>	<i>T ST</i>
Gelatin	69.0 μm	–	$5.6\text{--}6.48 \times 10^{-11} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	–	15
Soy Protein	0.160 mm	–	$0.6 \text{ mm g m}^{-2} \text{ h}^{-1} \text{ KPa}^{-1}$	–	1
Whey Protein	0.126 mm	–	$5.18 \times 10^{-9} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	–	9
Edible Wax	-	–	$1.26 \times 10^{-12} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$	317.23	5

Similarly, protein-based packaging materials offer an eco-friendly alternative with a lower carbon footprint. However, they present challenges, such as limited mechanical strength and high gas permeability under humid conditions ([Hadidi et al., 2022](#)). Proteins sourced from plants and animals are utilized, with their origin affecting the cost and practicality of the final product ([Asgher et al., 2020](#); [Zubair & Ullah, 2020](#)). Animal-derived proteins like whey and gelatin consist of diverse polypeptides that provide unique functionalities in packaging applications. In contrast, “plant-based proteins” such as wheat gluten and zein are considered more sustainable options.

Zein, a corn protein, is “insoluble in water” and demonstrates excellent water resistance due to its low acidic and essential amino acid content. Studies show that keratin bio-composite films from chicken feathers enhance “mechanical strength and antimicrobial properties,” making them suitable for FP ([Oluba et al., 2021](#)). Additionally, composite films combining chicken feather keratin and pomelo peel pectin exhibit improved

moisture absorption and water vapor permeability ([Das et al., 2018](#)). Developing biomaterial-based packaging systems is essential to extending shelf life and reducing waste. For successful commercial adoption, these materials must balance performance, sustainability, cost-efficiency, and scalability. Meeting regulatory standards while ensuring functionality and environmental goals remains a key focus for advancing BiM in FP.

6.3 MAJOR ACTIVE BIOMATERIALS USED FOR SMPC

6.3.1 Polysaccharide-Based Biomaterials

6.3.1.1 Chitosan

Chitosan, a “natural biopolymer” and “cationic polysaccharide” made up of “glucosamine units,” is derived through the “deacetylation” of chitin, which consists of N-acetyl-d-glucosamine units ([Rebouças et al., 2023](#)). Chitosan-based packaging films exhibit excellent mechanical strength and low gas permeability, though their high moisture affinity increases water vapor permeability ([Chaudhary et al., 2022](#)). Researchers have explored blending chitosan with other natural biopolymers or incorporating bioactive compounds to address these limitations. For instance, [Muthulakshmi et al. \(2021\)](#) reported that combining chitosan with microbial extracellular polymeric substances enhanced gas exchange properties, making the films more effective for food preservation. Ultrasonic treatment of rice starch and chitosan films further improved their mechanical (increased by 30% for tensile strength and 8% elongation at break), barrier (two times lower than control), and optical properties, with rice starch forming cross-linkages that reduced water seepage while increasing “tensile strength” and “elongation at break” ([Brodnjak & Todorova, 2018](#)).

Eco-friendly and cost-effective chitosan-based bio-nanocomposites have been developed, offering enhanced physical and chemical properties. For instance, incorporating “cerium” and “zirconium oxide” nanoparticles into “chitosan/gelatin” films has improved their thermal and mechanical stability ([Ahmed et al., 2021](#)). A solution was prepared by magnetically stirring a mixture containing 50 mL of distilled water, 2% acetic acid, and the chitosan required at 25°C for 3 hours. This chitosan solution was then combined with a pre-prepared gelatin solution. Meanwhile, varying concentrations of CeO₄Zr nanoparticles (0, 1, 3, 5, 10, 20, and 30 wt%) were sonicated in 10 mL of distilled water for 2 hours before being gradually introduced into the mixture, followed by an additional 1-hour stirring. The solutions were evenly distributed into hydrophobic polystyrene Petri dishes (10 cm in diameter) and left to dry at 40°C for 24 hours to form the desired films. The mechanical properties exhibited significant enhancement, even at the highest nanoparticle concentration (30%), indicating effective dispersion of the metal-oxide nanoparticles within the polymer matrix. Additionally, the incorporation of nanoparticles led to an increase in the glass transition temperature ([Ahmed et al., 2021](#)). Similarly, adding titanium oxide nanoparticles provides chitosan films with photocatalytic, antimicrobial, and UV-blocking properties, enhancing their durability ([Sani et al., 2022](#); [Ding et al., 2024](#)). In another study, chitosan coatings infused with “zinc oxide nanoparticles” demonstrated significant antimicrobial activity against *Listeria monocytogenes* (number reduced by 1.5 log CFU/g) in vacuum-sealed white brined cheese, reducing bacterial levels on the cheese surface and interior at refrigeration temperatures ([Olaimat et al., 2022](#)). Furthermore, “chitosan-based composite films” exhibit improved compatibility, thermal stability, and adhesion properties ([Chaudhary et al., 2022](#)). Chitosan-gelatin biocomposite films, for example, show higher tensile strength, UV barrier properties, and reduced water vapor permeability ([Ahmed & Ikram, 2016](#)). Combining chitosan with various proteins, carbohydrates, EOs, and other additives can tailor biomaterial-based packaging materials to meet specific needs. These

innovations contribute to developing sustainable packaging solutions that enhance food safety and support environmental conservation.

6.3.1.2 Cellulose

Various cellulose derivatives, such as carboxymethyl cellulose, methylcellulose, hydroxypropyl cellulose, cellulose acetate, and hydroxypropyl methylcellulose, are commonly used in edible food packaging ([Yekta et al., 2023](#)). Antimicrobial and antioxidant agents can also enhance these derivatives to boost their performance. For instance, bilayer films from cellulose acetate and hydroxyethyl cellulose infused with resveratrol or its complex with hydroxypropyl- γ -cyclodextrin have shown significant antimicrobial activity. Films containing resveratrol alone exhibited more potent inhibitory effects than those with the inclusion complex, making them practical for poultry meat packaging and preventing foodborne pathogens ([Silva et al., 2016](#)).

The functionality of cellulose in food packaging can be further enhanced by producing nanocellulose fibers. Nanocellulose is obtained through top-down techniques, such as mechanical or chemically assisted deconstruction ([Mahmoud et al., 2024](#)). A study by [Carvalho et al. \(2018\)](#) showed that incorporating 4% (w/w) CNFs into nanocomposites reduced water vapor permeability (WVP) by about 30% and enhanced mechanical strength (10.75% more than the control) as the CNF concentration increased. These findings highlight the potential of CNCs and their functional derivatives, sourced from renewable natural materials, to create sustainable and biodegradable packaging solutions for food applications.

6.3.1.3 Starch

Starch, a typical “plant-derived polysaccharide,” is frequently utilized in the production of films because of its low cost and practical film-forming abilities ([Pei et al., 2024](#); [Roy et al., 2024](#)). Despite these advantages, starch has drawbacks, such as its susceptibility to water transmission, brittleness, and lack of mechanical strength. These challenges often require

improvements, such as blending with lipids or other biopolymers ([Bangar et al., 2021](#)). One research study investigated starch-based films incorporating cranberry powder, examining their microstructure, sensory characteristics, thermal stability, mechanical properties, and ascorbic acid content. It was found that cranberry powder enhanced the sensory qualities of the films while protecting the ascorbic acid from degradation due to light, heat, and oxidation, thereby maintaining its stability ([Matta Fakhouri et al., 2019](#)). Mango kernel starch has also been explored for food preservation; one study demonstrated its ability to prolong the shelf life of tomatoes by slowing the ripening process, affecting parameters like soluble solids concentration, weight loss, tartaric acid content, and fruit firmness ([Nawab et al., 2017](#)). The coating solution was prepared by gelatinizing mango kernel starch (4.0 g per 100 mL of solution) in distilled water while continuously stirring on a hot plate. Plasticizers—glycerol, sorbitol, and a 1:1 mixture of the two (50% starch weight, dry basis)—were incorporated into the solution and stirred for 30 min. Fresh tomatoes were immersed in the coating mixture for 30 seconds, air-dried, and stored at 25°C and 60% relative humidity for 20 days in a controlled atmosphere chamber. Applying these edible coatings altered the internal atmosphere by increasing CO₂ levels and/or reducing O₂ levels, slowing the respiration rate and minimizing ethylene production. A lower respiration rate, in turn, delayed metabolic activity, reducing soluble solids. The findings revealed that all coating formulations effectively reduced fruit respiration rates, consequently curbing the excessive breakdown of organic acids during respiration. Among the plasticizers, sorbitol-based coatings exhibited superior efficacy in slowing down metabolic processes, likely due to their enhanced barrier properties against oxygen permeation. The study also indicated that weight loss in tomatoes increased over the storage period for all samples. However, coated fruits exhibited significantly lower weight loss than uncoated ones, with sorbitol-containing coatings offering the highest level of protection. Additionally, coated samples demonstrated better resistance to firmness loss. They retained their texture throughout the storage period, with sorbitol-based coatings performing the best, followed

by the combination of glycerol and sorbitol, and finally, glycerol alone ([Nawab et al., 2017](#)).

6.3.1.4 Carrageenan

Carrageenan is frequently utilized to make edible films and coatings. For instance, [Yadav and Chiu \(2019\)](#) developed nanocomposite films reinforced with cellulose nanocrystals (CNC) in κ -carrageenan, which resulted in better packaging properties. The incorporation of CNC at concentrations ranging from 0 wt.% to 7.0 wt.% resulted in an enhancement of the films' mechanical properties, with tensile strength increasing from 38.33 ± 3.79 MPa to 52.73 ± 0.70 MPa and elongation at break improving from $21.50 \pm 3.72\%$ to $28.27 \pm 2.39\%$. In another study, [Martiny et al. \(2020\)](#) demonstrated that adding olive leaf extract to carrageenan films led to a 54% reduction in water vapor permeability and increased film flexibility. Recent advancements include the development of color-changing nanocomposite films containing silver nanoparticles (AgNPs) and anthocyanins from red grape skins, as [You et al. \(2022\)](#) reported. These films were designed to monitor the freshness of marine fish. The anthocyanins provide pH-responsive color changes, while AgNPs impart antibacterial properties. These films exhibited improved mechanical strength and UV-blocking properties. The tensile strength and elongation at break of these films increased by 10.95% and 7.42% than control film. Additionally, the films retained color stability for up to 240 days under UV exposure at 25°C, with the color change correlating with changes in “total volatile elemental nitrogen (TVBN)” levels during fish storage. These innovations highlight the potential of carrageenan-based nanocomposites for FP, especially for indicating freshness and enhancing preservation.

6.3.2 Protein-Based Biomaterials

6.3.2.1 Collagen

Recent studies have explored nanotechnology-enhanced approaches for reinforcing collagen, offering promising advancements ([Tripathy et al., 2023](#); [Tian et al., 2024](#)). Incorporating nanofillers into collagen-based materials can significantly improve their mechanical properties, barrier effectiveness, antioxidant capacity, sensor capabilities, and antimicrobial activity against pathogens. For example, collagen casings used in fermented sausage production have been shown to enhance quality attributes such as hardness (from 1042.0 to 2668.9 per gram) and gumminess (from 911.8 to 1407.6 per gram) while reducing biogenic amine content ([Yan et al., 2022](#)). [Abdullah et al. \(2022\)](#) recently developed nanocomposite films by adding iron oxide (IO) and graphene oxide (GO) nanoparticles. Including both types of nanoparticles notably increased the hydrophobicity (water contact angle rising from 77.2° to 84.4°). These nanoparticles also improved the films' antioxidant activity (95.8%) and antibacterial efficacy, exhibiting a 23.8 mm inhibition zone. These results underscore the potential of nanofillers to enhance the functional properties of collagen-based films, making them ideal candidates for food processing applications.

6.3.2.2 Gelatin

Gelatin, a prominent protein extracted from animal tissues such as skins and bones, is renowned for its ability to form films, biocompatibility, adhesion properties, and function as a barrier against oxygen and odors. It also boasts strong gel strength, viscosity, and elasticity ([Zhang et al., 2024e](#)). [Shankar et al. \(2019\)](#) explored the impact of melanin nanoparticles (MNPs) on gelatin films' mechanical and chemical properties, revealing that the concentration of MNPs influenced the final properties. Including MNPs notably improved the films' "UV-blocking capacity (completely blocked in the case of 1 wt% of MNP incorporated gelatin film)," "mechanical (mechanical strength increased from 33.6 to 46.5 MPa) and thermal stability (decomposition temperature increased from 310°C to 321°C for nanocomposite films)," "water vapor barrier (WVB) properties (decreased from 1.04 to 0.78×10^{-9} g.m/m².Pa.s)," and antioxidant activity (increased

from 5.7% to 56.5%). Furthermore, nanofillers have been employed to add sensing functions to “gelatin films.” [Pereira et al. \(2020\)](#) developed “gelatin films” embedded with ZnO nanoparticles to detect changes in relative humidity for FP applications. These nanoparticles enhanced water vapor permeability (WVP) and significantly boosted the film’s sensitivity to humidity, achieving a sensitivity of 99.47%.

6.3.2.3 Soy Protein

Soy protein (SP) ingredients are primarily sourced from a combination of “globulin” and “albumin” found in soybeans ([Zhao et al., 2023b](#); [Rout & Srivastay, 2024](#)). SP isolate films are known for their smooth, flexible, and transparent characteristics, distinguishing them from other protein-based films ([Xu et al., 2022](#)). Furthermore, SPI films offer effective oxygen barrier properties in low-moisture environments. However, they face challenges, including low mechanical strength, poor heat resistance, and potential allergenic properties compared to LDPE ([Asgher et al., 2020](#)). [Koshy et al. \(2022\)](#) recently created SPI films enhanced with silver nanoparticles, carbon dots, and chitin nanowhiskers (CNWs) ([Koshy et al., 2022](#)). Their study investigated the impact of incorporating silver nanoparticles and varying CNW concentrations (2–10%) on SPI films’ mechanical and physicochemical properties. CNWs and silver nanoparticles improved the films’ thermal stability and mechanical strength (tensile strength increased from 4.67 to 15.45 MPa). Additionally, this combination imparted excellent antifungal properties (percentage inhibition of radial growth value of 62.5%) to the films, enhancing their potential for extending the shelf life of food products.

6.3.2.4 Whey Protein (WP)

Due to their excellent film-forming capabilities, whey proteins exhibit notable functional properties such as transparency, flexibility, and resistance to oil and gases under low humidity. A recent study by [Al-Hayali and Cagri-Mehmetoglu \(2022\)](#) examined the effects of iron oxide nanoparticles on WP

isolate films. Their findings revealed that adding IONPs increased tensile strength by approximately 2.6 MPa, along with a decrease in water vapor permeability and elongation. Conversely, incorporating YSR did not significantly alter the film properties or introduce antibacterial activity ([Al-Hayali & Cagri-Mehmetoglu, 2022](#)). [Pino et al. \(2021\)](#) developed whey protein nanocomposites containing zinc oxide (ZnO) nanoparticles, which exhibited antibacterial properties for FP. These films showed a concentration-dependent antimicrobial effect, particularly against *S. epidermidis*, owing to the properties of ZnO nanoparticles, with an average size of 30 nm and a specific surface area of 49.5 m²/g ([Pino et al., 2021](#)). This demonstrates that protein-based bio-nanocomposites could be highly effective for FP applications.

6.3.3 Lipid-Based Biomaterials

6.3.3.1 Edible Wax

“Edible waxes” are derived from animal and plant sources ([Tijani et al., 2024](#)). Several studies have investigated using wax coatings to prevent dehydration in “fruits and vegetables.” For example, composite films or wax-enhanced formulations, such as “chitosan-beeswax coatings,” extended the shelf life of “sapodilla fruits” by up to 17 days compared to untreated ones. Adding “beeswax” to “chitosan” coatings helped reduce microbial contamination, minimize weight loss, and preserve the fruit’s firmness and color ([Pashova, 2023](#)). When “carnauba wax” was incorporated into “arrowroot starch-based edible films” using emulsion technology, it improved the films’ hydrophobicity and provided superior light barrier properties, making them suitable for FP ([de Oliveira Filho et al., 2020](#)). Incorporating carnauba wax as a microemulsion increased the film’s opacity, whereas including nanoemulsions reduced opacity. This phenomenon occurs because larger particles scatter light more effectively, enhancing emulsions’ opacity. Uncoated blackberries, on the other hand, started to show signs of decay within just four days, as reported by

[Ascencio-Arteaga et al. \(2022\)](#). The coated fruits exhibited substantially less decay compared to the uncoated ones, with reductions ranging from 1.2 to 2.2 times on day 4 and 1.3 to 1.9 times on day 6. Natural waxes are highly valued in the food industry due to their ability to minimize stickiness, improve surface aesthetics, and align with the growing consumer preference for environmentally friendly alternatives.

6.3.3.2 Edible Fats/Oils

When edible oils are incorporated into films, they can enhance surface smoothness and improve the reflective properties of the film-air interface by filling in microscopic voids created during film formation ([Yin et al., 2023b](#)). For instance, coatings made from plant-based oils such as olive and ginger oils have been found to help extend the shelf life of fruits like oranges and tomatoes by reducing spoilage and minimizing weight loss ([Atta et al., 2022](#)). The role of oils in film formulations has been extensively studied. [Wardak et al. \(2021\)](#) investigated the impact of “sunflower oil” on “starch-based films.” They discovered that its inclusion reduced “elongation at break” from 4% to 2.5% and decreased “water vapor permeability” from 4.5 to 3 g.mm.m⁻².d.Pa × 10⁻⁷ as compared to pure starch films. In another study, [Galus \(2018\)](#) demonstrated that adding rapeseed oil to soy protein isolate films improved elongation at the break (from 3.95% to 4.19%) by acting as a plasticizer within the “hydrocolloid matrix.” The increased hydrophobicity of rapeseed oil also reduced the films’ water vapor permeability, enhancing their barrier and mechanical properties. Similarly, [Ma et al. \(2016\)](#) showed that incorporating oleic acid into tara gum-based edible films decreased water vapor permeability and improved surface contact angles. A tara gum (TG) solution (0.75% w/v) was prepared in water and combined with varying concentrations of oleic acid (OA) (0–20% w/w). The mixture was then dried to form films. As the OA concentration increased from 0% to 20%, the water vapor permeability (WVP) of the TG films progressively declined from 0.694 to 0.610, 0.561, 0.528, and 0.526 × 10⁻¹⁰ g s⁻¹ m⁻¹ Pa⁻¹. Additionally, the elongation percentage initially rose

from 2.7% to 8.5% at 10% OA concentration before decreasing to 2.85% at 20% OA. The contact angle measurements revealed an increase from 76.75° to 107.28° as OA content increased from 0 to 20 wt%, surpassing 90° at 10 wt% OA. These findings suggest that the film surface exhibited hydrophobic characteristics, indicating that OA incorporation effectively reduced moisture absorption in TG films.

6.3.3.3 Resins

Resins, such as those derived from terpenes and wood, are natural substances that can be used as materials for film formation ([H. Zhang et al., 2024](#)). For example, resin-based coatings have enhanced the gloss and transparency of green chilies and tomatoes ([Cheng et al., 2021](#)). Shellac resin, which comes from animal sources, is particularly valued for its natural properties, biodegradability, and suitability for food applications ([Devi et al., 2024](#)). To improve “shellac films” mechanical and functional qualities, approaches such as reducing particle size or crosslinking shellac molecules have been explored ([Prawatborisut et al., 2019](#)). For instance, [Soradech et al. \(2017\)](#) developed shellac-based films containing varying levels of gelatin. Among the various gelatin concentrations tested, a 40% gelatin formulation was optimal for use as an edible film coating. Consequently, a composite film comprising 60% shellac and 40% gelatin, with or without adding 5% PEG 400, was selected as a coating solution to enhance the shelf life of bananas. They found that increasing the gelatin content strengthened the films and enhanced their surface tension, making them more effective at protecting the product, thereby extending their shelf life. The surface tension of the composite polymer demonstrated a significant increase ($p < 0.05$) from 40.55 mN/m to 52.12 mN/m when the gelatin content was raised to 50% w/w, suggesting a higher degree of hydrophilicity in the polymer solution.

6.4 CONCEPT OF SMART PACKAGING

6.4.1 pH Indicators

pH indicators detect significant changes in food pH through visible color variations. These pH changes in packaged food typically result from microbial activity, enzymatic processes, or chemical reactions ([Subash & Perumalsamy, 2023](#)). Natural pigments are generally preferred over synthetic dyes for this purpose ([Figure 6.1](#)). The mechanism behind colorimetric pH sensors relies on proton exchange between the pigments and the surrounding medium ([Alizadeh-Sani et al., 2021](#); [Verma et al., 2022](#); [Kaur et al., 2024](#)). Additionally, certain pH sensors use specific volatile compounds to indicate changes in food quality. pH-responsive films are often created using natural pigments and biopolymers, including proteins such as gelatin, corn protein, and SPI, as well as polysaccharides like starch, chitosan, carrageenan, pectin, and various gums, with the addition of plasticizers to form the films ([Table 6.2](#)). Materials like chitosan, starch, gelatin, and natural gums have been extensively researched due to their excellent properties ([Kumar et al., 2024](#)). Intelligent packaging systems that respond to pH changes, especially for meat products, have garnered significant attention. Meat spoilage produces total volatile elemental nitrogen (TVBN) due to “protein breakdown” by enzymes and bacteria, making pH a crucial factor for assessing freshness ([Siddiqui et al., 2022](#)). For example, [Hu et al. \(2021\)](#) developed a “pH-responsive antibacterial packaging film” using PVA/PAA combined with “aminoethyl-phloretin (AEP).” The AEP is integrated into the PVA/PAA matrix through hydrogen bonding, resulting in a pH-sensitive release mechanism that follows a first-order kinetic model. As the pH decreases, the dominant release mechanism gradually transitions from polymer relaxation to Fickian diffusion. The PVA/PAA-AEP films exhibit antioxidant and antimicrobial properties, which are influenced by the AEP content. Additionally, their antibacterial effectiveness is more pronounced against *Listeria*

monocytogenes and *Staphylococcus aureus* compared to *Escherichia coli*. Notably, the PVA/PAA3-AEP3 film extends the shelf life of pork by four days at 25°C, maintaining TVB-N levels below 25 mg/100 g, highlighting its promising application in intelligent food packaging ([Hu et al., 2021](#)). Similarly, an intelligent packaging film from heat-treated soy protein isolate and gellan gum incorporating *Clitoria ternatea* (CT) extract was designed by [Wu et al. \(2021\)](#). This film released anthocyanins in response to increased pH, providing antibacterial and antioxidant properties while monitoring shrimp freshness through color changes associated with anthocyanins. The incorporation of gum improved the stability of CT anthocyanins and facilitated their controlled release from the gum film in response to pH variations. These intelligent films exhibited a color change as the total volatile elemental nitrogen (TVBN) levels increased, correlating with the progressive spoilage of shrimp. This indicates their potential utility in real-time seafood freshness monitoring ([Wu et al., 2021](#)). These improvements result from better pigment dispersion, intermolecular hydrogen bonding, and enhanced structural and crystalline properties ([Kumar et al., 2024](#)).

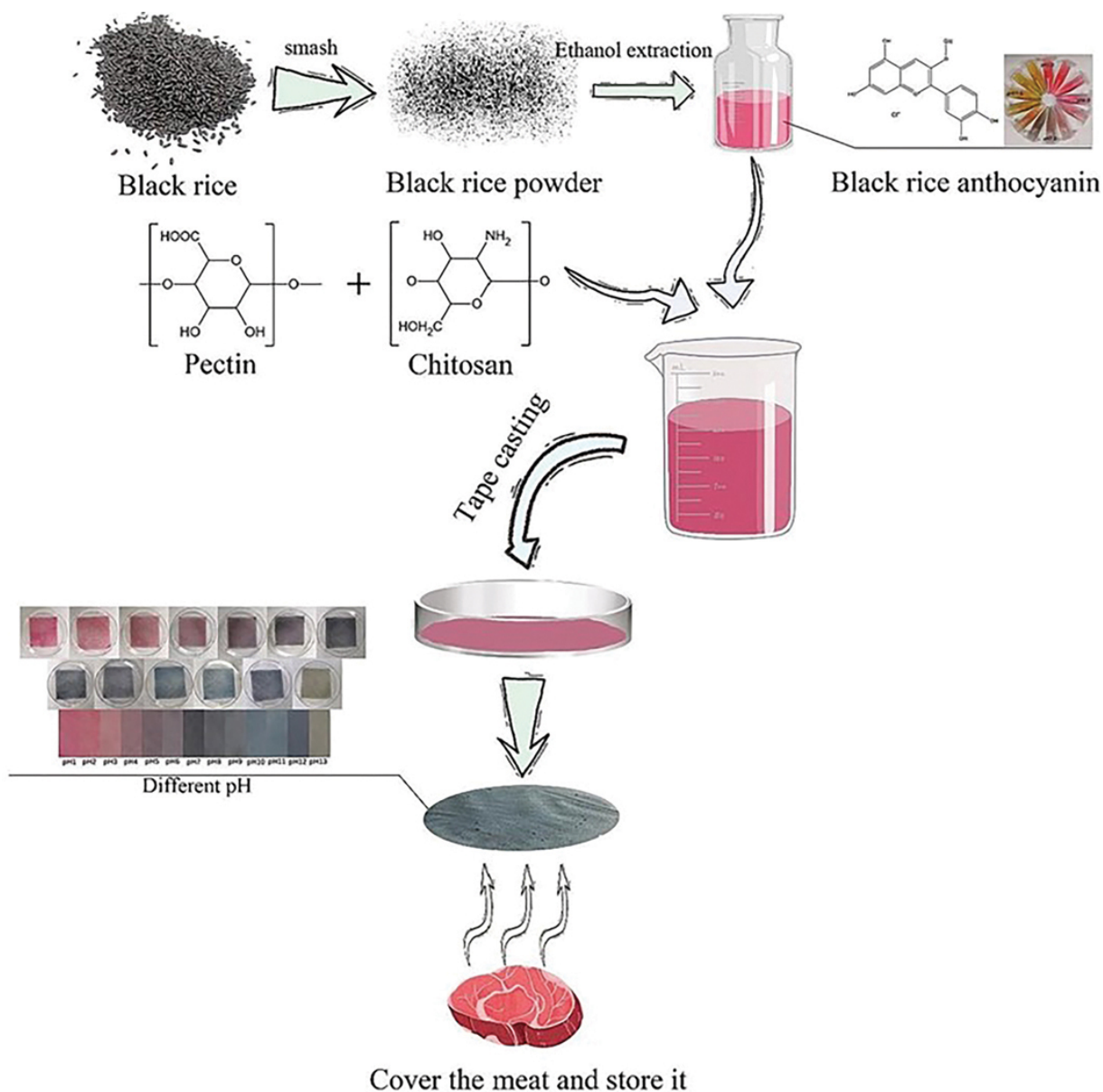


FIGURE 6.1 pH-responsive smart packaging ([Zeng et al., 2023](#)) (Reprint with permission). [↗](#)

TABLE 6.2 Recent Advances in Development of Smart Packaging Material

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
κ-carrageenan/straw lignin	The smart film exhibited	pH	1–

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	excellent responses in pH and ammonia.		
Potato starch/anthocyanins/bacterial nanocellulose	The color of the packaging material shifts from red/pink to purple, blue, and green when the samples are immersed in various buffer solutions (pH 2.0–10.5).	pH	4–
Nisin/gelatin (GA)/pullulan (PUL)	The film demonstrated pH-sensitive behavior in response to the rise in biogenic amines during shrimp spoilage, highlighting its potential as a freshness indicator.	pH	2–
Carboxymethyl cellulose/gelatin	The films exhibited pH-	pH	2–

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	sensitive color properties, with enhanced anthocyanin (ATH) color stability achieved through the formation of ATH-Al ³⁺ chelates.		
Pectin/chitosa/black rice anthocyanins	FBR ATH is suitable for developing pH-sensitive smart FP films that serve as intelligent indicators to monitor food freshness.	pH	1–
Polyvinyl alcohol (PVA)	A noticeable variation in fluorescence color is observed in response to H ₂ S released from spoiled	Gas (Hydrogen sulfide)	LO 4.20

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	meat, highlighting the potential use of the film as a detector for meat freshness.		
Hydroxypropyl methylcellulose (HPMC) and sodium alginate (SA)	The film successfully tracked food quality by exhibiting a color change as the food began to spoil.	Gas (Ammonia)	6.10. mg/ { 6.10. mg/ {
Carboxymethyl cellulose/gum xanthan	The low-concentration ammonia-sensitive indicator films exhibited more noticeable color changes compared to the high-concentration films.	Gas (Ammonia)	4 mg/ at 1 d; wh stor 4°
Starch/polyaniline (PANI)	The starch/PANI films exhibited	Gas (Ammonia)	LO 245

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	a color shift from green to blue when exposed to ammonia vapor.		
Dialdehyde starch (DAS/chitosan oligosaccharide/poly (lactic acid) (PLA)	An amylase-responsive nanofiber membrane enabled a controlled, on-demand release of antimicrobial agents, offering a cost-effective solution to inhibit spoilage microorganisms and demonstrating substantial potential for use in advanced antimicrobial active packaging materials.	Enzyme (Amylase)	0.5 mg/

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
Collagen/delphinidin	The film exhibited noticeable color transitions from purplish-red to greyish-blue as the fish spoiled, indicating that laccase holds promising potential for applications in active and intelligent FP.	Enzyme (Laccase)	
Pectin-coated poly (lactic acid)	The pectinase-sensitive nanofiber membrane shows promising potential for use in the development of active or SmPc systems.	Enzyme (pectinase)	1– mg/
Cellulose acetate/LDH@cellulose (CALC)	This research demonstrates that the CALC membrane	Humidity	40

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAT</i>
	developed, along with its associated design approach, can be applied to create various other packaging materials suitable for research and food industry application.		
2-hydroxypropyl-β-cyclodextrin	The shelf life of the meat increased by nearly 3 days compared to the control group.	Humidity	33 98
β-CD-MOF/carvacrol@zein (BCCZ)	This research offers significant insights and shows potential for the development and commercial use of safe,	Humidity	43

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAT</i>
	eco-friendly packaging films that help preserve freshness.		
Gelatin hydrogel and ethyl cellulose	The bilayer film successfully preserved the postharvest quality of white button mushrooms, extending their shelf life to 7 days when stored at room temperature.	Humidity	60
Hydroxypropyl methylcellulose (HPMC) and sodium alginate (SA)	This study contributes to the advancement of natural, edible packaging films, improving their safety and monitoring features, which	Temperature	25

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	represents a noteworthy step forward in the field of smart FP technology.		
Poly (3,4-ethylene dioxythiophene)/poly(styrenesulfonate)	At 40°C, the total release could surpass 60%, resulting in a 95% reduction in free radicals. The suggested device has the potential to be integrated into active FP.	Temperature	40
Polyvinyl alcohol (PVA)	This study could serve as a valuable resource for developing thermosensitive drug-loaded nanofibers designed for controlled drug release.	Temperature	42

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAT</i>
Chitosan/pectin	The CN/PE 15% multi-active films, designed using spectral stacking theory, effectively blocked UV light in the outer layer, demonstrated strong protection for NATA under UV exposure over various durations, and ensured prolonged and sustained bacterial inhibition in the inner layer.	Light (UV)	25 n
Gelatin	The shelf life of beef was prolonged through the application of a	Light (Blue light)	435

<i>BIOMATERIALS COMBINATION</i>	<i>PACKAGING MATERIAL PROPERTIES</i>	<i>STIMULI SOURCES</i>	<i>RAI</i>
	blue light coating.		
Wheat straw cellulose fibers (CF) and cellulose nanofibers (CNF)	Composite packaging films effectively preserved the quality and monitored spoilage in high-protein products, particularly shrimp, by controlling the release of biogenic amines.	Light (UV)	254

6.4.2 Gas Indicators

Monitoring the gas composition within the headspace of a package is crucial for maintaining food freshness and safety. During spoilage or aging, specific gases are emitted into the headspace, and their permeation through packaging can alter concentrations, potentially leading to food deterioration ([Mirza Alizadeh et al., 2021](#); [Akhila et al., 2024](#)). Fresh produce, for example, releases ethylene gas during respiration, which serves as an indicator of its freshness and quality. Oxygen permeation into FP can

trigger chemical reactions and oxidative degradation, contributing to spoilage ([Subash & Perumalsamy, 2023](#)).

In addition to oxygen, microbial contamination poses significant risks to food safety. The potential for oxidation, microbial spoilage, and degradation underscores the need for smart biodegradable films capable of detecting and indicating the presence of specific gases, thereby ensuring food quality and safety ([Sohail et al., 2018](#)). Modern SmPc integrates indicators for gases such as O₂, CO₂, H₂S, ethylene, and other volatile compounds ([Table 6.2](#)). These gas sensors function based on the chemical reactivity of natural pigments, with increasing gas concentrations causing visible color changes. For instance, anthocyanins, gelatins, and carotenoids degrade in ammonia, shifting from purple to green and eventually yellow ([Musso et al., 2019](#)). Gas indicators are available as labels, printable inks, tablets, or films, and are particularly common in vacuum and modified atmosphere packaging. These indicators help detect even minimal concentrations of unwanted gases, protecting the product throughout its shelf life ([Luo et al., 2023](#)). For example, an intelligent biodegradable packaging film made from curcumin, polyvinyl alcohol, and tara gum was used to monitor shrimp freshness by detecting ammonia gas ([Ma et al., 2017](#)) ([Figure 6.2](#)). As the concentration of curcumin increased from 0.1% to 0.5%, the film's light transmittance at 600 nm slightly declined, reducing from 32.90% to 27.45%. A noticeable color shift occurred in the presence of NH₃ within 1 to 3 minutes. Additionally, elevated relative humidity levels enhanced the color response. The release of ammonia was indicated by a distinct color change in the film, shifting from yellow to brown. The film was tested for shrimp spoilage detection to assess its practical application, revealing a distinct color change. These findings suggest that the film holds potential as a sensor for applications in the food industry.

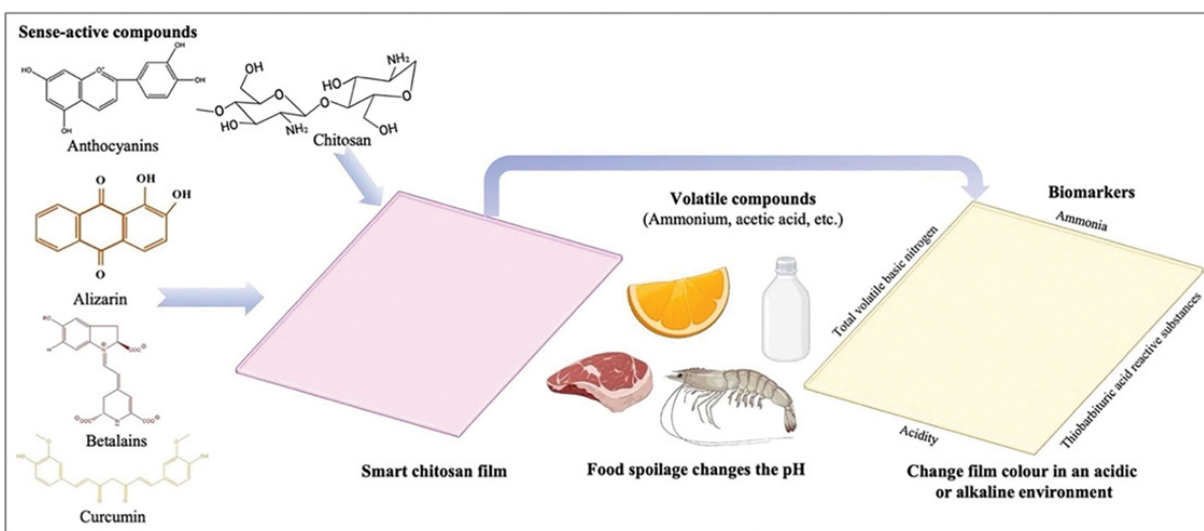


FIGURE 6.2 Gas-sensing smart packaging ([Bhowmik et al., 2024](#)). [↗](#)

6.4.3 Enzyme-Responsive Smart Packaging

Microorganisms significantly cause spoilage across various food categories, including fresh produce, meat products, and baked goods. They produce enzymes such as cellulase, protease, pectinase, and amylase, which contribute to the degradation of food quality ([Jangra & Srivastava, 2023](#); [Bautista-Hernández et al., 2024](#); [Verma et al., 2024](#)). Leveraging these enzymes as triggers to hydrolyze carrier materials and release functional molecules offers a promising approach to developing innovative active packaging systems ([Table 6.2](#)) ([Alshangiti et al., 2023](#); [Tripathy et al., 2024](#)).

Recently, enzyme-responsive smart active packaging has garnered attention, with systems developed to react to enzymes produced by bacteria or fungi. Fungi, for example, are a major cause of spoilage in fruits and vegetables. They secrete extracellular enzymes that break down the host's cell wall, weakening its defenses and accelerating decay ([Das et al., 2021](#)). Based on this concept, [Min et al. \(2022\)](#) designed polyethyleneimine (PEI)-modified porous poly(lactic acid) (PLA) nanofibers loaded with thymol and coated with a pectin layer, which serves as a gatekeeper ([Figure 6.3](#)). The fabricated nanofiber membrane effectively suppressed the growth of *E. coli*, *S. aureus*, and *Bacillus subtilis* by more than 95%, demonstrating

remarkable antifungal activity, particularly against *Aspergillus niger*. The controlled release of thymol (THY) from the pectin-coated porous nanofiber membrane (THY@PLA-PEI-Pectin) was activated by pectinase, an enzyme secreted by microorganisms associated with food spoilage. When citrus fruits inoculated with *A. niger* spores were wrapped in these nanofibers, only slight disease spots developed, indicating potential for further improvement by adjusting enzyme concentration and fungal inoculation levels. Moreover, the biocompatible THY@PLA-PEI-Pectin membrane extended the shelf life of citrus fruits. Consequently, this pectinase-responsive nanofiber membrane holds excellent potential for advanced active and smart packaging systems applications ([Min et al., 2022](#)).

In a similar approach, researchers exploited the enzymatic activity of *Escherichia coli* O157, which produces “ β -glucuronidase (β -G)” and “serine protease,” to create “silk fibroin nanofibers” embedded with cinnamaldehyde-loaded nanoparticles. These nanofibers showed effective preservation properties for beef products ([Lin et al., 2022](#)). For enzyme-responsive packaging systems to be effective, it is crucial to consider the specific microorganisms and their enzyme profiles related to food spoilage. The compatibility of the substrate and the environmental conditions required to facilitate enzymatic hydrolysis must be carefully assessed during material design.

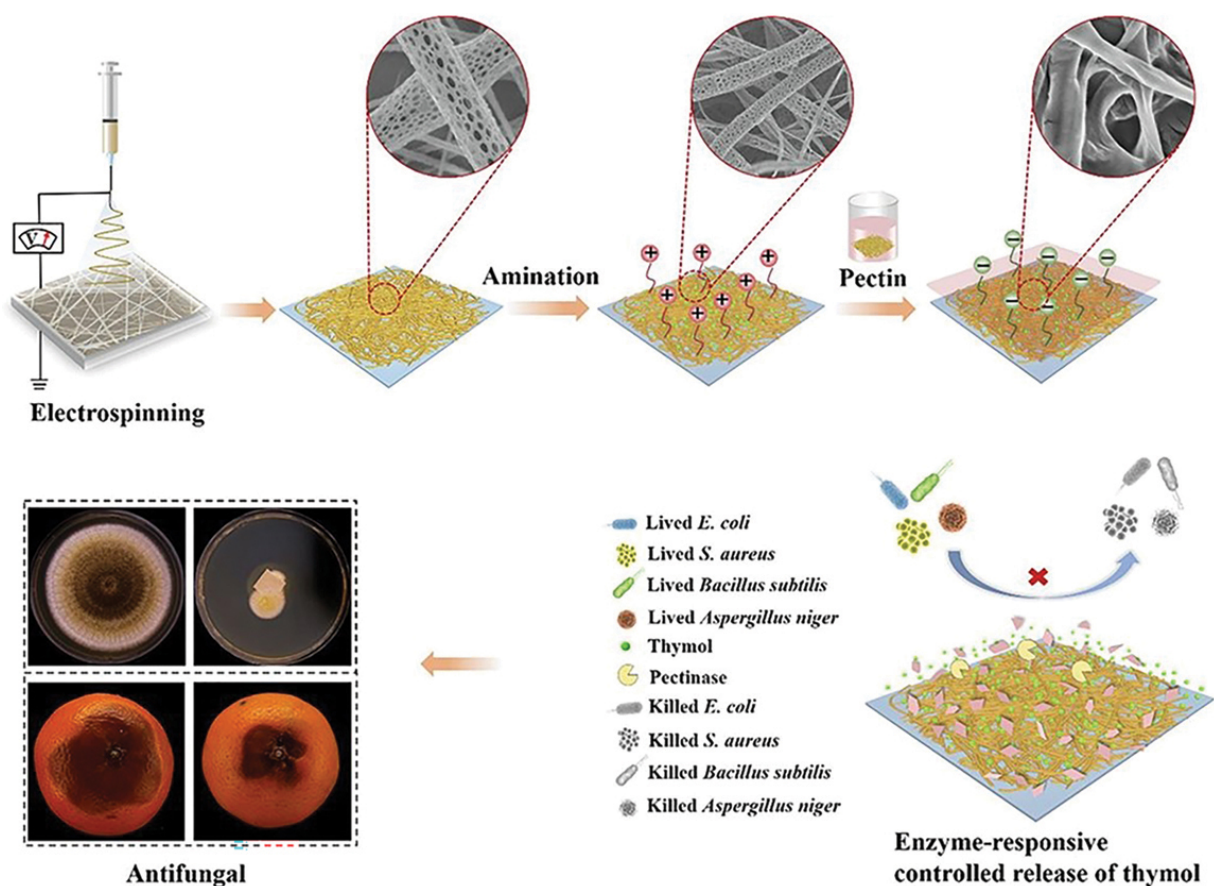


FIGURE 6.3 Enzyme-responsive smart packaging (Min et al., 2022) (Reprint with permission). ↵

6.4.4 Humidity-Based Smart Packaging

FP systems designed for items like meat, fruits, and vegetables often operate in environments with relative humidity (RH) of 90% or higher, which, unfortunately, also promotes microbial growth (Qu et al., 2022). This high-humidity condition, however, provides an opportunity to develop humidity-responsive SmPc that releases functional molecules on demand (Table 6.2). Cyclodextrins (CDs) are one example of materials that enable such controlled release. Under high humidity, the cyclodextrin inclusion complexes (CD-ICs) dissociate due to weakened H₂ bonding between the CDs and the functional molecules, facilitating release (Du et al., 2022).

Chlorine dioxide (ClO₂) is a powerful antimicrobial agent commonly used in food preservation, illustrating the concept of humidity-responsive packaging. Several active packaging systems have been developed to

release “ClO₂” in response to changes in humidity ([Figure 6.4](#)). Hydrophilic polymers, which absorb water vapor and swell, can increase gas permeability and speed up the release of active agents. For example, [Wong et al. \(2022\)](#) created a “nanofiber film” by “electrospinning” a PEG, PLA, and carvacrol solution. This film exhibited a humidity-triggered release of carvacrol. When incorporated into food packaging under high humidity conditions, the nanofibers exhibited a sustained and substantial release of carvacrol into the headspace. Visual inspection revealed that the shelf life of strawberries increased by an additional two days when stored with the optimized nanofibers. Furthermore, after three days of application, the strawberries packaged with nanofibers showed significantly lower yeast and mold counts (4.28 ± 0.34 log CFU/g) than those without nanofibers (5.22 ± 0.47 log CFU/g). In a similar approach, [Zhang et al. \(2022\)](#) designed a packaging material modeled after leaf stomata, using “ethylene vinyl alcohol copolymer (EVOH)” as the outer layer and thymol as the core, produced through coaxial electrospinning. The release of thymol was influenced by relative humidity (RH), with nanofibers exhibiting a higher release rate at 90% RH compared to 30% RH. Moreover, these functionalized nanofibers demonstrated strong antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus* in vitro and good biocompatibility. When applied to fruit preservation, the nanofiber film effectively prolonged the shelf life of strawberries. The sensory evaluation further indicated that strawberries treated with thymol/EVOH nanofibers maintained a highly acceptable flavor ([Zhang et al., 2022](#)). To optimize such systems, it is important to choose suitable carriers that limit unnecessary exposure to reactants, ensuring controlled and efficient release in humidity-responsive active packaging.

temperature are crucial for developing advanced release systems ([Du et al., 2023b](#)). “Time-Temperature Indicators (TTIs)” are commonly used to reflect irreversible changes, such as color or shape alterations, based on a product’s temperature history. These indicators mimic quality changes in food products subjected to similar temperature exposures ([Table 6.2](#)) ([L. Yang, Yuan, et al., 2024](#)). TTIs monitor parameters such as biological activity, acid-base reactions, melting points, polymerization, and spore formation, with natural pigments often employed to signal changes through color variation ([Figure 6.5](#)) ([Subash & Perumalsamy, 2023](#)). For example, [Xia et al. \(2023\)](#) developed a thermosensitive polylactic acid (PLA) nanofiber film infused with lemon essential oil and coated with PNIPAAm. The PNIPAAm layer regulated the release of LEO, slowing it down at temperatures below its lower critical solution temperature (32°C). Once the temperature surpassed 32°C, the PNIPAAm layer transitioned from a chain-like structure to a globular form, leading to an accelerated LEO release, though slower than PLA/LEO. This temperature-responsive release mechanism in the PLA/LEO/PNIPAAm membrane extended the duration of LEO activity. As a result, the PLA/LEO/PNIPAAm system effectively preserved blackberries’ visual appeal and nutritional quality under fluctuating storage conditions. Similarly, [Douaki et al. \(2022\)](#) produced a “poly (propylene carbonate) (PPC) nanofiber mat loaded with cinnamon essential oil (CEO)” and layered with PEDOT and PNIPAAm. TTIs indicate spoilage through enzymatic, microbial, electrochemical, or chemical reactions, with their activation and response often modeled mathematically to predict shelf life accurately ([Y. Ma et al., 2022](#)).

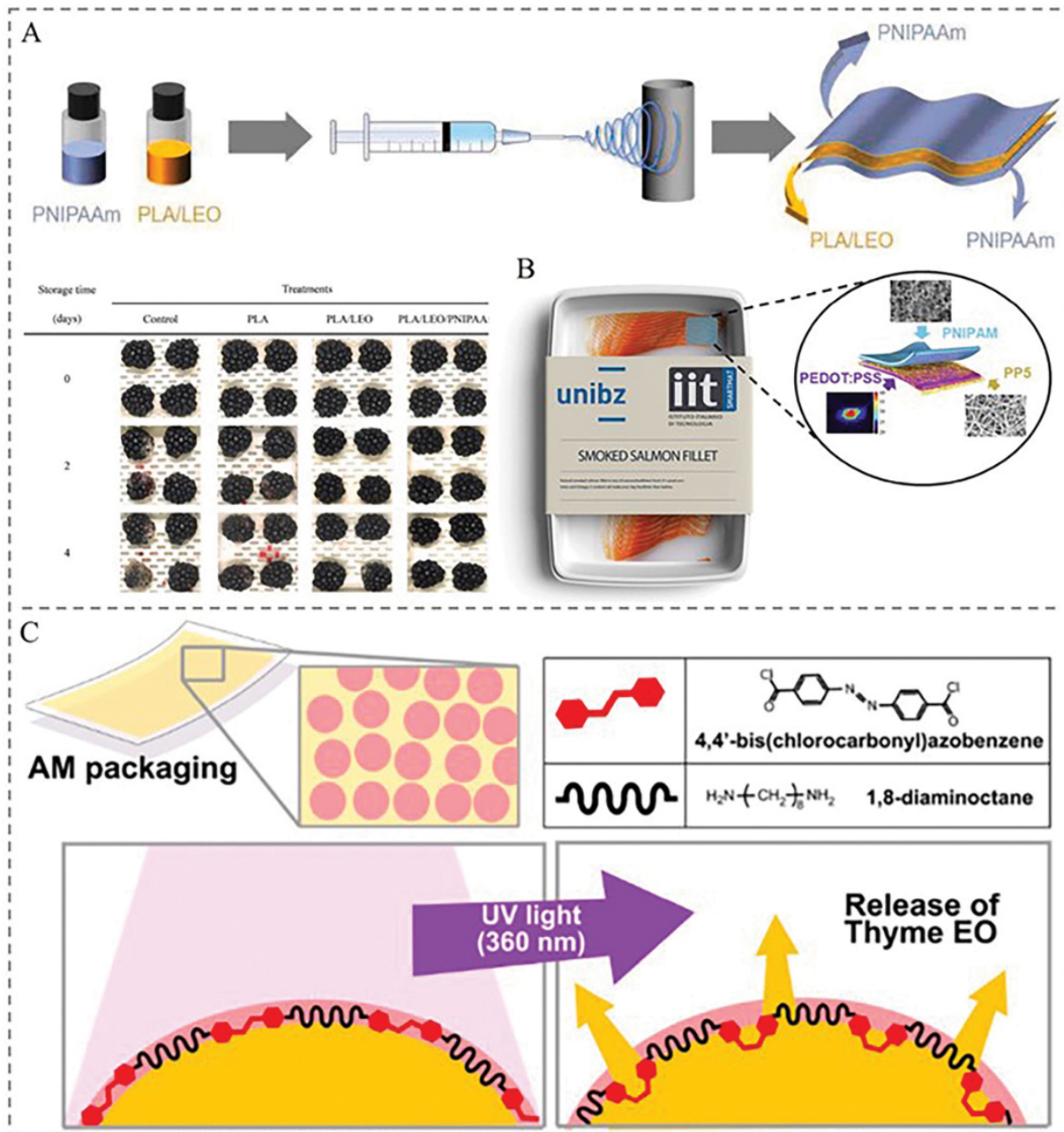


FIGURE 6.5 Temperature-responsive and light-responsive active packaging. Temperature-responsive active packaging of (A) lemon essential oil and (B) cinnamon essential oil based on PNIPAm (C) UV light triggered the isomerization of the azobenzene chain segment and thus accelerated thymol release ([Du et al., 2023](#)) (Reprint with permission). [↗](#)

► Description

6.4.6 Light-Sensitive Smart Packaging

Fewer studies have explored systems triggered by light among the various types of intelligent packaging. When exposed to light, these systems release reactive oxygen species (ROS) or other functional molecules, making them a promising avenue for innovative active packaging solutions. Packaging materials capable of generating ROS under light are categorized as light-responsive systems. Nanoparticles like berberine and vitamin K3 have been incorporated into antimicrobial packaging ([Sheng et al., 2020](#); [K. Ma et al., 2022](#)). By carefully controlling light exposure or combining ROS production with other antimicrobial agents, synergistic effects can enhance functionality ([Table 6.2](#)) ([Basavegowda & Baek, 2021](#)).

Developing intelligent, active packaging films with controlled-release properties that respond to external stimuli is a crucial advancement in food preservation. In this regard, [Ning et al. \(2025\)](#) designed a light-responsive carrier material, PBA-IRMOF-3, by integrating azobenzene 4-carboxylic acid (PBA) with a photosensitive azobenzene group into an isoreticular metal-organic framework material-3 (IRMOF-3). To create a light-responsive, controlled-release active film, the researchers incorporated PBA-IRMOF-3 loaded with carvacrol (CA) into a sodium alginate (SA) matrix, forming PMC@SA. When exposed to alternating ultraviolet (UV) and visible (Vis) light, the azobenzene group in PBA-IRMOF-3 underwent structural isomerization, functioning as an “impeller-stirring” mechanism that facilitated the release of CA. As a result, the PMC@SA film exhibited controlled-release behavior under light exposure. Additionally, the film demonstrated high hydrophobicity, with a water contact angle of $69.67 \pm 1.21^\circ$, along with exceptional water vapor barrier properties (water vapor transmission rate: $559.68 \pm 5.99 \text{ g}\cdot\text{d}^{-1}\cdot\text{m}^{-2}$) and strong light-blocking capacity (nearly zero transmittance in the 250–380 nm range). The PMC@SA film significantly enhanced meat quality when applied to pork preservation, especially after UV light treatment ([Ning et al., 2025](#)). Moreover, a study by [X. Yang, Sheng, et al. \(2024\)](#) investigated the antimicrobial efficiency of polylactic acid (PLA)-coated pullulan/chitosan/homojunction g-C₃N₄ (Pul/CS/HCN) films when subjected to visible light exposure. These films achieved log reductions of

3.43 and 3.11 against *Escherichia coli* and methicillin-resistant *Staphylococcus aureus* (MRSA), respectively, within 2 hours. The outstanding antimicrobial activity was attributed to the combined effects of chitosan (CS) and the reactive oxygen species (ROS) generated by HCN. Furthermore, strawberries packaged with PLA@Pul/CS/HCN films exhibited reduced quality deterioration and extended shelf life after visible light exposure. Similarly, [Wang et al. \(2023b\)](#) evaluated the effectiveness of a chitosan (CS) and sodium alginate (SA) packaging film embedded with QDs@ZIF-8 nanoparticles (NPs) in preserving kiwi fruit. The formulated films demonstrated strong antibacterial activity, an inhibition ratio exceeding 99%, and effective ethylene scavenging properties, removing over 40% of ethylene. These functional properties were attributed to the synergistic action of ROS generation under visible light and the high surface area of ZIF-8, contributing to prolonged fruit freshness. Furthermore, [Ni et al. \(2021\)](#) developed a novel self-activating nanocomposite film composed of chitosan and negatively charged graphitic carbon nitride fabricated via one-step electrostatic self-assembly. Under visible light exposure, the antibacterial efficacy of this film reached $99.8 \pm 0.26\%$ against *E. coli* and $99.9 \pm 0.04\%$ against *S. aureus*. Additionally, it successfully extended the shelf life of tangerines to 24 days. Hemolysis and cytotoxicity tests confirmed that the film was biocompatible and safe for food packaging applications. [Marturano et al. \(2019\)](#) developed light-responsive nanocapsules containing thymol, which were applied as coatings for commercial films ([Figure 6.5](#)). UV light (360 nm) triggered conformational changes in the azobenzene segments within the nanocapsule shells, accelerating thymol release ([Marturano et al., 2019](#)). However, to ensure practical applications, further research is needed to evaluate the stability of the packaging material under light exposure and its suitability across various stages of food distribution.

6.5 APPLICATION OF BIOMATERIAL-BASED SMART PACKAGING IN FOOD

6.5.1 Dairy Product

Milk products are highly susceptible to spoilage due to their nutrient-dense composition, which promotes microbial growth. SmPc can protect dairy products while providing valuable insights into their condition and storage history ([Upadhyay et al., 2024](#)). As milk is stored, microbial activity produces lactic acid, causing the milk's pH to drop. Fresh cow's milk typically has a slightly acidic pH ranging from 6.4 to 6.8, but this stability decreases as spoilage progresses ([Lelis et al., 2024](#)). To address this, “active edible films” have been created to improve the quality and extend the “shelf life” of dairy products by preventing chemical degradation and microbial contamination ([Table 6.3](#)). Including antimicrobial and “antioxidant agents,” such as “essential oils,” further enhances the preservation properties of these films ([Yin et al., 2023b](#)). To further advance SmPc, researchers have explored biomaterial-based films that utilize the color-changing properties of anthocyanins in response to pH shifts. [Bandyopadhyay et al. \(2020\)](#) developed a film using bacterial cellulose, guar gum, polyvinyl pyrrolidone, and CMC, infused with red cabbage anthocyanins, which allowed for freshness monitoring of Gouda cheese. Similarly, [Liu et al. \(2019\)](#) created a “pH-responsive film” using “κ-carrageenan” and anthocyanins from *Lycium ruthenicum*. This film demonstrated color changes from pink to yellow (pH 2.0–10.0), with microbial spoilage indicated by a shift to a darker pink hue. These studies highlight the potential of pH-responsive SmPc as a reliable tool for monitoring dairy freshness. These indicators offer a promising approach for real-time quality control in dairy products by evaluating the relationship between pH, acidity, and microbial growth.

6.5.2 Meat Product

Meat products are prone to spoilage during processing and storage due to lipid oxidation, microbial activity, and enzymatic degradation. These spoilage mechanisms can negatively impact the products’ texture, flavor, appearance, and safety, emphasizing the importance of effective preservation techniques ([Zhu et al., 2024](#)). Biomaterial-based SmPc, developed from natural sources and integrated with advanced technologies, is commonly utilized for packaging various meat products, including red meat, poultry, fish, and processed meats. These packaging materials contribute to improved product safety and extended shelf life, as outlined in [Table 6.3](#) ([Upadhyay et al., 2024](#)). [Abelti et al. \(2022\)](#) investigated using biomaterial-based polymers combined with bioactive compounds for packaging fish. Key indicators of meat spoilage include alterations in color, flavor, texture, and pH, and damaged or leaking packaging often leads to consumer rejection and financial losses ([Abelti et al., 2022](#)). [Khodaei et al. \(2023\)](#) highlighted recent innovations in meat packaging technologies, emphasizing the need to optimize intelligent components in innovative packaging to maintain quality, nutritional value, and cost-effectiveness.

One such innovation involves using cellulose derived from “*Acetobacter xylinum*” to create biomaterial-based SmPc that can detect quality changes and help preserve meat freshness ([Dirpan et al., 2022](#)). For instance, a packaging system that uses bromothymol blue solution changes color from “orange to dark green” as beef begins to spoil. Additionally, studies have shown that incorporating high concentrations of garlic extract into “active packaging” can extend meat shelf life by up to 4 hours. In conclusion, biomaterial-based SmPc significantly improves meat safety and quality by reducing the need for active substances, limiting particle migration, and minimizing the risk of bacterial contamination during industrial processing.

TABLE 6.3 Food Applications of Smart Packaging Materials Developed fr

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJ</i>
<i>COMPOSITION INCORPORATED APPLICATION CONDITION FINDI</i>				

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION</i>	<i>INCORPORATED</i>	<i>APPLICATION</i>	<i>CONDITION</i>	
Sodium alginate-chitosan	Anthocyanins	Milk	Temp: 25°C	The color of the film's surface shifted from purple to the milk's fresh color. The freshness declined after the 72-h monitoring period.
Chitosan-polyvinyl alcohol	<i>Thymus vulgaris</i> ; <i>Calamintha nepeta</i> ; <i>Camellia sinensis</i> ; and <i>Origanum vulgare</i> essential oils	Cheese	Temp: 4–5°C RH: 36%	The spoilage of microorganisms was less than the control group.
Whey protein concentrate-glycerol	-	Cheese	Temp: 4°C Time: 7 days	Nutritional values of the cheese maintained.
Sodium alginate	<i>O. basilicum</i> L, <i>R. officinalis</i> L. <i>A. herba alba</i> Asso. <i>M. pulegium</i> L.	Cheese	Temp: 5–7°C Time: 10 days	The biodegradation of the coating decreased the weight loss and hardness of the cheese compared with the control sample without the coating.

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION</i>	<i>INCORPORATED</i>	<i>APPLICATION</i>	<i>CONDITION</i>	
Starch-glycerol	Black carrot anthocyanins	Milk	Temp: 20°C	The color in the film showed a correlation with the physicochemical and microbial alterations in milk and its spoilage
Zein/tannic acid	Oregano essential oil	Shrimp	Temp: 4°C	Maintained freshness of shrimp for 10 days
Carboxymethyl cellulose	-	Pastrami	Temp: 4°C	The color of the film showed a change from red to brown-yellow-brown after 10 days due to the development of volatile nitrogenous compounds, allowing for the consumption and assessment of the freshness and edibility of products in time

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION</i>	<i>INCORPORATED</i>	<i>APPLICATION</i>	<i>CONDITION</i>	
Methyl cellulose	-	Chicken breast	Temp: 4°C Time: 10 days Air composition: 80% N ₂ :20% O ₂	Packaging enhance shelf life
Sodium alginate-chitosan	Red beetroot anthocyanin	Chicken fillet	Temp: 25°C	It improved quality, extended shelf life, reduced microbial growth of chicken when applied a coating
Rice starch	Curcumin	Chicken and fish	Temp: 4°C	Preservation product freshness
Cassava starch	Pomegranate peel powder	Lamb meat	Temp: 25°C	The film transition period reduced to 60% over the course of storage at 25°C
Ginger starch	-	Ground beef	Temp: 4°C	The starch successfully prevented oxidative rancidity of ground

FILM COMPOSITION	BIOACTIVE INCORPORATED	FOOD APPLICATION	STORAGE CONDITION	MAJOR FINDINGS
				samples in the refrigerator
Chitosan-coix seed starch	<i>Artemisia annua</i> essential oil	Pork	Temp: 5°C Time: 11 days	Maintain freshness of products
Potato starch/apple peel pectin	<i>Zataria multiflora</i> essential oil	Quail meat	Temp: 4°C Time: 12 days	The film had the greatest effect on the shelf life of quail
Maize starch	Grape juice	Chicken breast fillets	Temp: 4°C Time: 8 days	Coating chicken fillets with edible film made from grape juice improved oxidative stability and inhibited microbial growth at cold storage
Chitosan-starch	<i>Thymus kotschyanus</i> essential oil	Beef	Temp: 4°C Time: 21 days	Beef samples wrapped with the film exhibited extended shelf life
Chitosan-AgNPs	Dragon fruit stem extract	Strawberry	Temp: room temperature Time: 5 days	The shelf life of strawberry was prolonged

<i>FILM COMPOSITION</i>	<i>BIOACTIVE INCORPORATED</i>	<i>FOOD APPLICATION</i>	<i>STORAGE CONDITION</i>	<i>MAJOR FINDINGS</i>
				they are wrapped composite
Chitosan-poly (vinyl alcohol)	-	Strawberry	-	The composite film demonstrates outstanding photocatalytic antibacterial and preservation capabilities
Polyvinyl alcohol (PA)-soluble starch (SS)-polyethylene glycol bis (3-aminopropyl) ether	Blueberry anthocyanin (BA), curcumin (CU)	Strawberry	Temp: 24°C	The film monitored freshness product sensing release volatile through storage period
Sodium alginate	<i>Dendrobium officinale</i> polysaccharides	Grape	Temp: 25°C Time: 14 days	The composite film demonstrates significant inhibition growth of <i>Escherichia coli</i> and <i>Staphylococcus aureus</i>

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION</i>	<i>INCORPORATED</i>	<i>APPLICATION</i>	<i>CONDITION</i>	
Sodium alginate	Ginger essential oil	Mango	Temp: -80°C Time: 11 days	The film maintained postharvest quality of mango
Pectin, sodium alginate, and xanthan gum	Blueberry anthocyanin extract	Blueberry	Temp: -1°C to 25°C Time: 11 days	The film preserved product freshness
Sodium alginate	-	Banana	Time: 5 days	The film significantly improved anti-browning effect, prolonged shelf life of banana
Sodium alginate-tannin	-	Fresh-cut apple	Time: 7 days	The apple packed with films did not brown during 7 days
Sodium alginate-ZnO NPs	<i>Aloe vera</i>	Tomato	Time: 16 days	The prepared coating inhibited spoilage of tomato
Sodium alginate, gum arabic, glycerol	Natamycin	Sweet potato	Temp: 10°C RH: 60	The film effectively reduced

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION</i>	<i>INCORPORATED</i>	<i>APPLICATION</i>	<i>CONDITION</i>	
				physiological and quality alterations in sweet potato during storage. Storage allowing to maintain excellent process quality after 120 days of storage.
Sodium alginate	Aloe vera and frankincense oil	Green capsicum	Time: 16 days	The presence of active compounds with the ability to improve the blocking of physical and microbe inhibitory properties offer promising potential in food preservation.
Sodium alginate-carboxymethyl cellulose	Shallot onion waste extract	Fresh-cut apple and potato slices	Temp: 4°C Time: 16 days	The film inhibited browning and preserved

<i>FILM</i>	<i>BIOACTIVE</i>	<i>FOOD</i>	<i>STORAGE</i>	<i>MAJOR FINDINGS</i>
<i>COMPOSITION INCORPORATED APPLICATION CONDITION</i>				
				overall quality of the product more effective than the control

6.5.3 Fruits and Vegetables

Fruits and vegetables remain biologically active after harvest, undergoing various “physiological” and “biochemical” changes during storage. Two key challenges in this phase are “respiration” and “water loss,” which can significantly affect their quality and accelerate spoilage ([Gunny et al., 2024](#)). To prolong the shelf life of these products, packaging materials are designed to reduce water vapor and oxygen permeability ([Chen et al., 2024](#)). Researchers are investigating natural agents that can inhibit fruit ripening to minimize post-harvest decay. Biologically derived polymer packaging to coat fruits and vegetables effectively reduces deterioration and controls respiration by preventing moisture loss ([Table 6.3](#)) ([Nunes et al., 2023](#); [Perez-Vazquez et al., 2023](#)).

Chitosan, a biodegradable polymer with both “film-forming” and “antimicrobial properties,” is widely used in FP for fresh produce. It is commonly utilized to create edible packaging materials. For example, [Zhou et al. \(2021\)](#) demonstrated that chitosan films infused with 8% galangal essential oil (GEO) extended mango shelf life by nine days at room temperature. The films helped preserve mango firmness by reducing enzyme activity, respiration rates, and metabolic activity. GEO films also exhibited antimicrobial and barrier properties, slowing sugar hydrolysis and tissue respiration.

Protein-based edible films also act as protective barriers for fruits and vegetables, helping to prevent moisture loss and reduce respiration. Whey protein films, for example, offer good transparency and O₂ and CO₂

permeability. When applied to fresh-cut pears, WP films with 0.5% lemongrass essential oil helped maintain high polyphenol levels, which signified enhanced freshness. These coatings also preserved pear firmness by reducing cell wall degradation and pressure loss during storage. However, adding essential oils influenced sensory acceptability, suggesting the need for further optimization ([Galus et al., 2021](#)). Innovative packaging solutions, such as intelligent chitosan films, have been developed to predict fruit maturity by releasing volatile indicators like ethyl mercaptan, improving the management of storage times for fresh produce ([Shen et al., 2023a](#)). Additionally, combining chitosan matrices with nanofillers can overcome common packaging limitations, such as low thermal stability, weak barrier properties, limited mechanical strength, and poor transparency, enhancing the overall performance of the films ([Q. Zhang et al., 2024](#)).

6.6 CONSUMER AWARENESS AND REGULATORY CONCERNS FOR BIOMATERIAL-BASED SMART PACKAGING

As the food and packaging industries shift toward more sustainable alternatives, there has been growing consumer awareness and regulatory attention regarding biomaterial-based SmPc. These packaging solutions, which often utilize biodegradable or renewable materials combined with active or intelligent components, aim to meet environmental and functional requirements. For example, they can signal spoilage, monitor freshness, or even prolong shelf life through antimicrobial features. Despite the promising potential of BiM, there is some consumer hesitancy due to limited knowledge about their safety, effectiveness, and environmental consequences.

One of the main concerns among consumers is the health and safety of biomaterial-based packaging, especially when it involves organic materials

or the use of nanoparticles and chemical additives to enhance performance. Many worry about the possibility of harmful substances migrating into food or contamination risks. SmPc may also include sensors, indicators, or coatings, potentially leading to concerns about chemical residue consumption. These worries and a lack of familiarity with technical terms like “biomaterial-based” or “smart packaging” contribute to consumer reluctance. Therefore, educating the public about the safety and benefits of these packaging systems is essential to build trust and encourage their acceptance.

Another regulatory challenge lies in verifying the environmental claims of BiM, such as biodegradability or recyclability. False or exaggerated claims, often called “greenwashing,” can undermine consumer confidence and prompt scrutiny from regulatory bodies. In response, regulators increasingly emphasize the need for clear labeling, certification, and traceability to help consumers make well-informed decisions. Certifications and eco-labels can significantly boost consumer confidence, but it is also important to establish consistent standards and definitions for biodegradability and compostability. This would ensure that products labeled as such meet universal criteria. Increased transparency, supported by comprehensive sourcing, production, and disposal process information, will help alleviate consumer concerns. More enforceable regulatory standards will be vital to gaining consumer trust.

Collaboration among scientists, industry professionals, and regulatory agencies is essential to navigate these challenges successfully. This joint effort will address the complexities surrounding the safety, sustainability, and standardization of BiM-based SmPc. Developing adaptable regulations and maintaining transparent communication will be crucial for fostering a more informed consumer base, ultimately accelerating the adoption of sustainable packaging solutions.

6.7 CHALLENGES AND FUTURE PERSPECTIVE OF SMART PACKAGING

The challenges associated with active biomaterial (ABiM)-based SmPc are multifaceted, yet overcoming them could lead to significant progress in sustainable packaging. One key challenge is ensuring the stability and performance of BiM, particularly when integrating active components like antimicrobial agents, freshness indicators, or oxygen scavengers. These materials must adhere to food safety standards, remain effective throughout the product's shelf life, and ideally degrade in an environmentally friendly manner after use. In addition, scalability and cost-efficiency are concerns, as producing these advanced BiM often requires specialized processes and can be more expensive than traditional plastics. Consumer education and clear labeling are vital to building trust, as unfamiliarity and skepticism about biomaterial-based, active packaging materials can impede widespread acceptance. Looking ahead, research into natural polymers, nano-based delivery systems, and innovative manufacturing techniques could transform SmPc, making it more cost-effective, accessible, and efficient. Cooperation between industry, academic researchers, and regulatory bodies will be essential in developing standardized guidelines that ensure safety, performance, and environmental sustainability. As these technologies continue to evolve, the future of BiM-based SmPc will rely on striking a balance between innovation, regulatory requirements, and economic feasibility, paving the way for sustainable solutions that meet industry needs and consumer expectations.

6.8 CONCLUSIONS

Biomaterial-based SmPc presents a promising approach to tackling carbon neutrality and food safety challenges. Utilizing renewable resources and

advanced technologies contributes to sustainability and reduces food waste. Recent research has focused on developing “active” and “intelligent packaging” materials using natural, food-safe ingredients to enhance the functionality of packaging films. Studies have demonstrated that adding active agents can significantly improve film performance, while eco-friendly materials like starch and chitosan promote sustainability. Despite the progress in research and production technologies, it is crucial to conduct thorough life cycle, economic, industrial, and user perception assessments to understand these materials’ actual environmental and socioeconomic impacts. These biomaterial-based solutions can improve food distribution and consumption’s safety, efficiency, and sustainability. There is also an anticipation of more responsive SmPc tailored to specific stimuli and incorporating food-grade materials and functional molecules, bridging basic research with practical, real-world applications.

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Bio-Based Inks and Dyes for Food Packaging 7

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7.1 INTRODUCTION

7.1.1 Overview of Food Packaging and Sustainability

In the growing population and urbanization, food packaging is essential at stages of food production, such as transportation, storage, and consumption. Currently, there is a high demand for the protection and enhancement of food shelf life. Additionally, a large quantity of food is wasted or lost because of environmental factors such as oxidation, degradation, and contamination of food. The food and agriculture organization (FAO) of the UN first estimated in 2011 that a staggering 1.3 billion tones of edible food are lost or wasted globally each year, which is roughly one-third of all food produced for human consumption. This massive wastage occurs relatively evenly across the entire supply chain, with losses split into approximate thirds at the farm/production level, the distribution and processing stage, and the retail/consumer stage ([Gouthière, 2022](#)). Food packaging plays a

vital role in maintaining the original flavor, color, and nutritional properties of food for a longer time, even when food is exposed to adverse environmental conditions ([J. Han et al., 2018](#)). They serve to protect food from toxic contaminants and other external factors such as physical damage, microbial contamination, temperature changes, and humidity. Also, they play a critical role in preserving the safety and quality of food by enhancing the shelf life and reducing food loss and waste ([J. Han et al., 2018](#)). Other main functions include traceability, convenience, and conveying nutritional information about food. The main purpose of food packaging is to provide a cost-effective solution that meets quality standards and consumer expectations with less environmental impact. According to the FAO, food packaging safeguards food. Glass, metal, paper, and plastic are mainly used as packaging materials ([FAO, 1995](#)). The diverse range of plastics and their flowability and moldability enable the creation of different shapes, sheets, and structures. Cost-effectiveness, heat resistance, heat sealing, and barrier properties make them ideal materials for food packaging ([Fasake et al., 2021](#)). [Figure 7.1](#) shows the barrier properties of food packaging with respect to the external environment.

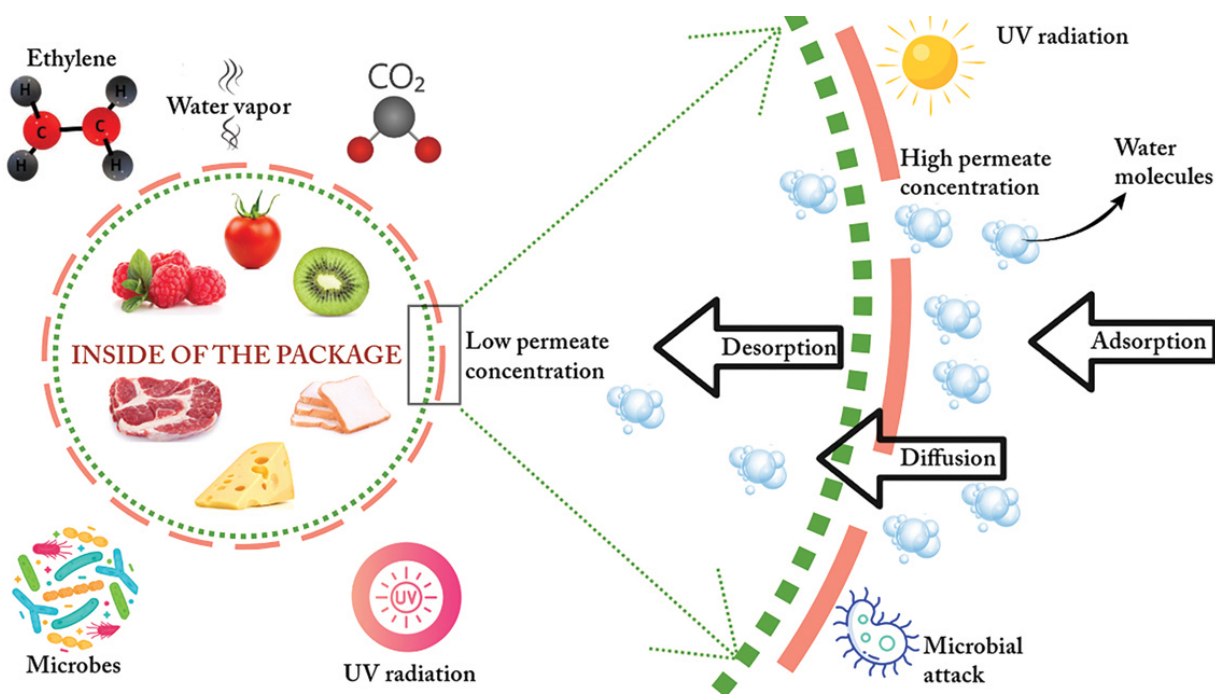


FIGURE 7.1 Barrier properties of food packaging with respect to external environment. 

7.1.2 Environmental Effects of Conventional Packaging

The environmental effect of traditional food packaging is a major concern, causing pollution, resource depletion, and greenhouse gas emissions. The U.S. Environmental Protection Agency (EPA) states that food and food packaging products constitute about 50% of all municipal solid trash in the United States. The majority of traditional food packaging is intended for one-time consumption, resulting in significant waste that remains unrecycled ([Chakori et al., 2021](#)). This trash frequently accumulates in landfills or becomes litter in natural habitats, such as oceans and waterways. The United Nations has designated plastic waste as a “planetary crisis,” emphasizing its harmful impact on marine organisms and ecosystems. Plastics may require hundreds to thousands of years to decompose, during which they disintegrate into microplastics that permeate the soil and aquatic systems, endangering species and potentially infiltrating the human food chain ([Hahladakis et al., 2018](#)). The plastic wastes deposited in the environment pose serious concerns to the ecological system. Additionally, entanglement in plastic refuse can cause injury or mortality to diverse marine and human species ([Geueke et al., 2018](#); [Groh et al., 2019](#)).

7.1.3 Functions of Ink and Dyes in Packaging

Inks and dyes in food packaging improve the appearance and the usage of packaging materials. They are mainly used for communication and marketing and also supply vital information, such as product specifications, expiry dates, and nutritional content while ensuring the packaging attracts consumers ([Das & Mandal, 2024](#)). However, [Figure 7.2](#) shows the classification of dyes based on structure, source, and applications. Inks and dyes are also important for improving the efficiency of intelligent and active packaging solutions. In intelligent packaging, pH-sensitive, thermochromic, or photochromic dyes are used to assess the food quality, including freshness or spoilage, via observable changes ([Dave et al., 2022](#)).

pH-sensitive dyes alter color in reaction to the emission of spoilage gases such as ammonia or carbon dioxide, providing a non-invasive method to assess food safety ([Abedi-Firoozjah et al., 2022](#)). Likewise, thermochromic dyes in temperature-sensitive packaging can signify whether products have been maintained within the requisite temperature range during storage or transport ([Thamrin et al., 2022](#)). On the other hand, active packaging incorporates functional inks with antioxidants, antimicrobials, or oxygen scavengers that have contact with the packaged food or its environment to improve preservation. Antioxidant-infused inks can neutralize free radicals, thereby decelerating the oxidative breakdown of lipids and proteins ([Sarfraz et al., 2024](#)). In inks, antimicrobial substances such as essential oils are added to inhibit the growth of microbes and enhance shelf life ([Sarfraz et al., 2024](#); [Hakim et al., 2024](#); [Dave et al., 2022](#)). Although there are various advantages to these inks, issues such as regulatory compliance, stability, and compatibility with various packaging materials are disadvantages ([Versino et al., 2023](#); [Hakim et al., 2024](#)). Therefore, the incorporation of functional inks and dyes is a method in food packaging that enhances aesthetics and supplies product information and functionality to satisfy contemporary consumer demands while tackling environmental issues.

<i>BASED ON STRUCTURE</i>	<i>BASED ON SOURCE</i>	<i>BASED ON APPLICATION</i>
■ Nitro and Nitroso dyes	■ Minerals	■ Acidic and basic dyes
■ Aniline yellow	■ Animals	■ Direct and vat dyes
■ Methyl orange	■ Leaves	■ Mordant dyes
■ Bismarck brown	■ Roots	■ Reactive dyes
■ Malachite green	■ Plants	■ Disperse dyes
■ Anthraquinone dyes	■ Fruits	■ Sulfur dyes

FIGURE 7.2 Classification of dyes based on structure, source, and applications. [↗](#)

7.1.4 Challenges Associated with Conventional Inks and Dyes

There are various demerits of conventional petroleum-based inks and dyes, mainly to humans and the environment. Also, most conventional inks contain pigments, binders, solvents, and additives from chemical sources. They generate volatile organic compounds not only while printing and drying but also after disposal ([R. Luo et al., 2022](#)). The generated volatile organic compounds, such as benzene and its derivatives, including toluene, ethylbenzene, and xylene, cause air pollution by creating photochemical smog, reducing the quality of air, causing chronic respiratory illness, and affecting the nervous system ([Patel et al., 2022](#); [Puttaswamy et al., 2021](#); [Zhu et al., 2024](#)). Additionally, the ink pigments, which are used to enhance durability and brilliant color patterns, show the presence of lead, chromium, and cadmium; are carcinogens; and also accumulate in the environment ([Prasanna et al., 2023](#)). The components of ink, such as solvents, plasticizers, binders, and byproducts, may migrate into the food, making it unsafe. For instance, in flexible packaging, the use of solvent-based ink contributes to the release of harmful compounds that are sometimes dangerous for consumption. Also, the extension of storage life leads to an increase in the migration of toxic compounds to food ([R. Luo et al., 2022](#)). Furthermore, conventional inks have less biodegradability, enhancing the process of recycling. The remaining ink is recycled via mechanical or chemical deinking processes. The deinking process, due to the hydrophobicity and other characteristics of conventional inks, causes inefficient recycling with lower-quality-covered compounds ([Zvonkina et al., 2014](#)).

The carbon footprints of conventional inks based on petrochemical sources are high since more greenhouse gases are emitted. This is because of the higher energy and the procedure of application of ink involved in the process. For instance, solvent-based inks require higher heat for drying, which in turn increases the quantity of greenhouse gases and carbon footprint. Also, printing errors occur due to the non-compatible nature of the formulation of ink with respect to different packaging, leading to

ineffective use and wastage of substances ([Jena et al., 2024](#)). Water-based and UV-curable inks are the best sustainable option to overcome these disadvantages. In water-based inks, organic solvents are used to reduce the volatile organic compounds. Similarly, UV-curable inks polymerize while they are under UV, thereby causing less energy consumption and no evaporation of the solvent. These sustainable solutions must strictly adhere to regulatory guidelines for adhesion, quality of printing, etc. ([Jena et al., 2024](#)).

7.2 BIO-BASED INKS AND DYES: AN OVERVIEW

7.2.1 Bio-Based Inks and Dyes: Definition

Bio-based inks and dyes are made from renewable biological resources, which may be plant-, animal-, or microbial-based. These include those polymers that are either directly extracted or chemically synthesized from other bio-based monomers, microbes, or genetically modified organisms. These materials typically have the property of biodegradability and are easily compostable. In packaging, inks, and dyes serve to provide color and visual appeal, yet they range greatly in chemical composition, application techniques, and functioning. Inks are generally suspended in a liquid with binders and other additives, whereas dyes are dissolved in a solvent. Another main difference is that ink creates a layer on the surface, whereas dyes get absorbed into the packaging material. Ink generally comprises a mixture of pigments or dyes, solvents, and various additions. The principal purpose of ink is to impart color, provide adhesion, and confer durability on a substrate, such as paper, plastic, or metal. The pigment in ink is often a solid, finely milled substance that remains insoluble in the solvent. Inks can be categorized into several categories, such as solvent-based, water-based, and UV-curable, based on the characteristics of the solvent and the curing

method ([Robert, 2015](#)). Dyes are substances that get dissolved in solvents and give color to food products. By absorption of light, dyes undergo molecular dispersion and impart color with exceptional transparency. Also, dyes produce more vibrant hues compared to pigments. They are generally used in cases where more precise intensity and transparency of color, including smart and active packaging such as pH, oxygen, and time-temperature indicators, are required. But, under the influence of heat, moisture, or solvents, dyes are not stable and undergo migration ([Martins et al., 2022](#)). The main difference between ink and dye is the solubility and dispersion. Inks form an opaque color because of their insolubility in water or other solvents and form a layer on the substrate. Also, inks last longer on the substrate compared to dyes. In contrast, dyes are organic compounds that are highly soluble in solvents, making them penetrate more into the substrate that is being colored ([Yadav et al., 2023](#)). Because of the higher degree of penetration, more vibrant and intense colors are formed. However, the main disadvantages of dyes are that they are less stable, fade more quickly, and are highly susceptible to external environmental factors. Another main concern is the migration of dye to the food in the food packaging caused by the leaching of dye used in the formulations ([Gürses et al., 2016](#)).

7.2.2 Composition

Generally, bio-based inks have to be compatible with the types of printers and printing technology used. The bio-based inks are generally designed to be compatible with particular printer types and printing technology employed. For instance, bio-based inks must be water-based for inkjet and screen printing, whereas both oil- and water-based inks can be used in flexography ([X. Luo, 2022](#)). The water-based inks are highly durable for glass surfaces, and solvent inks are ideal for metal cans and glass bottles. The formulation requires (1) the use of colorants/pigments such as carotenoids, chlorophyll, curcumin; (2) the binders that help ink adhere to the surface; (3) solvents that are often water-based or extracted from bio-

derived materials, reducing toxic emissions helps in dissolving ink components and maintaining consistency; and (4) additives such as bio-based waxes, drying agents and stabilizers may be included to enhance the performance characteristics such as durability, drying speed, and resistance to smudging ([Ozcan & Arman Kandirmaz, 2020](#)). These components create an eco-friendly alternative to petroleum-based inks, supporting sustainability in printing applications. On the other hand, bio-based dyes primarily consist of (1) colorants extracted from plants, fungi, and insects that provide a range of hues; (2) fixatives often derived from minerals such as alum or bio-sourced tannins, which improve dye bonding and color fastness; (3) solvents typically water or alcohol-based from renewable resources, which dissolve the dyes for application; and (4) additives such as natural thickeners, stabilizers, and preservatives, which enhance dye performance by improving coverage, preventing microbial growth and extending the shelf life ([Yadav et al., 2023](#); [Gürses et al., 2016](#)).

7.2.3 Environmental and Health Benefits

Bio-based inks and dyes are from renewable sources, which provide various health and environmental benefits. They provide lower levels of volatile organic compounds, heavy metals, and toxic chemicals. This reduces the risk of respiratory illness, exposure to toxic compounds by consumers, skin irritations, and long-term effects. Since they are biodegradable and highly non-toxic, the accumulation of contaminants and wastes in landfills and oceans is greatly reduced, which enhances the safety and health of human and marine life ([Halonen et al., 2020](#)). Moreover, their process of manufacturing typically involves the use of low energy and generates fewer greenhouse gas emissions, thus significantly reducing the harm to the environment and resulting in reduced carbon footprints. Additionally, these environmental characteristics provide bio-based inks and dyes a viable option for reducing ecological effects with an emphasis on human health ([Jena et al., 2024](#)).

7.3 TYPES OF BIO-BASED INKS AND DYES

7.3.1 Plant-Based Inks and Dyes

Plant-based inks used in printing are comprised of yellow lake, peacock blue, phthalocyanine green, and diary-like orange, which are made up of nitrogenous substances and use solvents, including linseed oil and soybean oil. The plant leaves, vegetables, fruits, and red wine are processed and then formulated into not only plant-based dyes but also pigments such as carotenoids, chlorophyll, betaines, anthocyanins, quercetin, etc. ([X. Luo et al., 2022](#); [Priyadarshi et al., 2021](#)). The sources and applications of bio-based dyes are pictorially presented in [Figure 7.3](#). They are extensively used in the areas of textiles, food packaging, and cosmetics. The market for natural inks and dyes is predicted to grow from 2021 to 2028 at a CAGR of 10.1%. These concerns make natural dyes a safer and eco-friendly alternative to conventional ones ([Chen et al., 2024](#); [Thakker & Sun, 2021](#)). There are very few chemical reactions involved in these, and hence, there is no problem with respect to the decomposition of waste.

The extraction of plant-based inks, such as betaine from beet, involves the process of cutting and blending with the solvent in the initial stages. This is followed by evaporating the solvent, where the dye is absorbed and centrifuged for the separation of unwanted particles. The resultant supernatant is dried in a vacuum oven ([Oladzadabbasabadi et al., 2022](#); [Saeed et al., 2024](#)). Additionally, betalains, which are found in beet juice, are highly stable and soluble in water and are used in plant-based ink applications, specifically in the area of flexible packaging where a vibrant hue is needed ([Khan & Liu, 2022](#)). Another pigment, anthocyanin, which is extracted from grapes, red cabbage, and berries, gives a characteristic red to purple color and is most predominantly used in food packaging applications ([Pereira et al., 2024](#)). Additionally, curcumin is one such pigment extracted from turmeric, which is from the root of curcuma plant. Curcumin is a yellow pigment with high antioxidant activity, giving it an organic option

for the packaging of food commodities ([Khankaew & Panichayupakaranant, 2023](#)). Chlorophyll is generally used along with other coloring substances to improve the appearance and fastness of the color. Chlorophyll is a green pigment obtained from green plants, providing improved aesthetics ([Nabi et al., 2023](#)). Due to the rising concerns about the usage of synthetic ones, plant-based inks and dyes are gaining attention among consumers. Although they are highly safe and sustainable, they still lack efficiency in terms of their performance, color uniformity, and cost associated with production ([Thakker & Sun, 2021](#)).

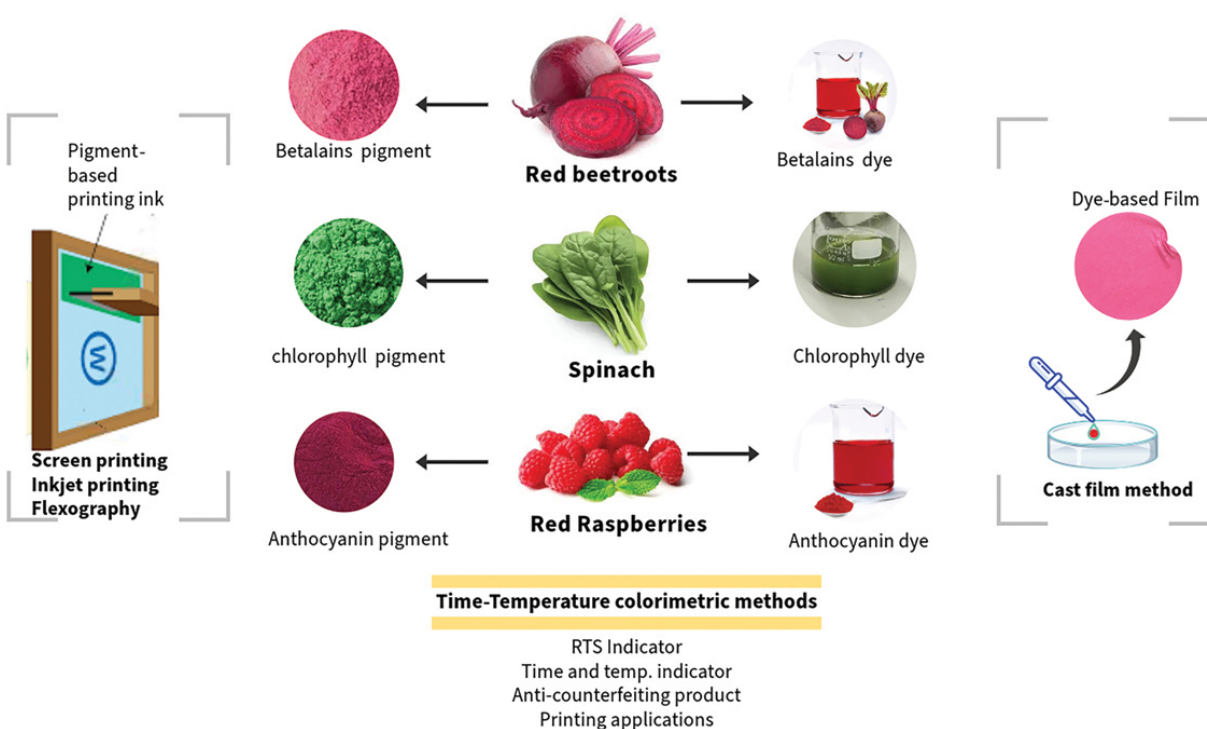


FIGURE 7.3 Bio-based dye sources and applications. [↗](#)

7.3.2 Microbe-Based Inks and Dyes

The natural dyes are extracted primarily from plants, insects, and microbes. However, planting the plants only for dyeing purposes causes higher investments. The batch production is difficult and highly unpredictable. Also, the usage of plants in the long term and large numbers causes the reduction of valuable resources ([Pavlović et al., 2022](#)). In order to tackle

this, researchers developed a methodology involving the extraction of color from microbes. Microbial stains are either synthesized from microbial cells or metabolic products as a result of microbial synthesis. Microbial strains are non-dependent on climate and offer a wide range of colors with distinct shades. Of these, bacterial strains are produced in relatively less time ([Tiwari, 2022](#)). These bacterial strains are produced by fermentation, extraction, and purification processes. Additionally, they are produced from wastes generated from agro-industrial residues. These residues are molasses, bagasse, wheat straw, and peels. This enhances sustainability and reduces waste generation, promoting a circular economy ([Gong et al., 2022](#)). Bacteria can produce various ranges of natural colors with respect to extreme conditions ([Venil et al., 2013](#)). The pigments produced are safe and also possess anti-inflammatory, antioxidant, antiallergic, and anticancer characteristics. These are used in textiles, food, cosmetics, and pharmaceutical applications ([Aman Mohammadi et al., 2022](#)).

Also, there are only a few bacterial pigments approved by the USFDA; they are indigo, riboflavin, lycopene, monascus, and astaxanthin ([Venil et al., 2020](#)). Other pigments of bacterial origin include violacein, indigoidine, melanin, carotenoids, prodigiosin, rhodopsin, pyocyanins, and flavins. First, violacein is a compound formed from tryptophan, which is isolated from *Chromobacterium violaceum*, *Pseudoalteromonas*, *Iodobacter*, etc. ([Tiwari, 2022](#)). The microbes capable of producing violacein are heterotrophic and mostly present in aquatic regions. Indigo dye is a blue pigment that is extensively used in the dyeing of textiles, capacitors, batteries, and medical applications. These are found in *Pseudomonas Indigofera*, *Erwinia*, *Corynebacterium*, and *Streptomyces*. Melanin is another pigment found in bacteria, fungi, and marine cephalopods. They are non-crystalline and impart a dark brown to black color. It is highly insoluble in organic and aqueous solvents, highly resistant to temperature present in *Rhizobium* and *Pseudomonas aeruginosa*, and exhibits biocompatibility. The vital fat-soluble pigments extracted from microbes are carotenoids, which are yellow to deep red in color ([Tiwari, 2022](#)). There are over 700 types of carotenoids found in nature. β -carotene is the pro-vitamin A that dissociates

the retinol molecules. Another carotenoid, astaxanthin from *Pontibacter korensis* AG6, exhibited antibacterial and antioxidant properties. *Serratia marcescens* produces prodigiosin, which has antibacterial, anticancer, antifungal, and anticancer characteristics. Some bacteria also produce secondary metabolites in the form of pigments. Also, algae oil, which is rich in omega-3 fatty acids, can be a better alternative for solvents in the formulation of inks, which enhances safety and sustainability ([Thakur et al., 2023](#)). In fungi, *Aspergillus* and *Penicillium* are capable of producing anthraquinone with vibrant colors and good thermal stability ([Daphedar et al., 2022](#)). Highly customized color spectra and intensities are possible with the use of microbial inks. Also, they possess greater stability with respect to heat, oxygen, and light, making them ideal for use in food applications ([Daphedar et al., 2022](#)). The use of these inks improves not only the appearance but also the functional properties. They contribute to the indicators of quality, freshness, and maturity, thereby enhancing the sensory properties. Bacteria such as *Bacillus* are capable of synthesizing pigments that change color according to pH and temperature ([Venil et al., 2013](#)). This helps in intelligent packaging by enhancing food safety and eliminating risks. Some of them also impart antimicrobial properties that enhance the shelf life of foods. They are highly sustainable and provide a promising solution with enhanced efficiency compared to those of plant-based ones ([Aman Mohammadi et al., 2022](#)).

7.4 TECHNOLOGICAL ADVANCEMENTS IN BIO-BASED INKS AND DYES

7.4.1 Techniques for the Production of Bio-Based Inks and Dyes

The main printing methods employed in bio-based inks and dyes are flexographic printing, inkjet printing, screen printing, etc. Screen printing is a traditional printing method that uses a mesh screen to apply ink on the

substrate material ([Mehrzhad et al., 2024a](#)). It involves the formation of a stencil/design on the screen that consists of a highly expanded mesh composed of materials such as nylon or polyester. Ink is deposited onto the screen and distributed throughout its surface with a squeegee, pushing the ink to flow through the exposed sections of the mesh onto the substrate beneath. The stencil defines the design, permitting the ink to flow in the intended pattern ([Puttipan & Khankaew, 2023](#)). It is employed for printing paper, ceramics, plastics, etc. Renowned for its resilience and vivid hues, screen printing is optimal for extensive manufacturing, although it is less appropriate for complex designs in comparison to digital methods ([Ding et al., 2020](#)).

Flexographic printing technology is used in food packaging due to its lower cost, versatility, and ability to produce a high-quality print on a wide variety of products ([Ding et al., 2020](#)). This technique employs soft and flexible printing plates where the top surface has raised pixels. Ink is applied via an anilox roll, which has a surface engraved with uniformly distributed small cells. The roll receives the ink from the chamber, and a doctor blade removes any excess, leaving the ink confined within the cells. The ink is then transferred to the raised pixels on the printing plate. During the process, the ink transfer occurs at a nip, where applied pressure enhances contact between the ink and the substrate. As the substrate exits the nip, the ink layer splits, transferring a portion of the ink to the substrate. Finally, the ink layer is dried by blowing hot air over its surface, which evaporates the solvent in the ink. The unique features of the food packaging meet the demands of aesthetics, functionality, and sustainability ([Robert, 2019](#)). The main advantage is the accommodation of a wide range of packaging materials such as plastic films, foils, paper, cardboard, etc. This printing allows the formation of flexible pouches into rigid cartons. The primary use of flexographic printing is flexible packaging, including plastic films and laminated materials used for snacks, frozen foods, sauces, and juices ([Robert, 2019](#)). The prints maintain integrity even in adverse conditions. This technology ensures that product information, such as nutritional information and expiry dates, is clearly displayed on the package

([Nasomboon et al., 2023](#)). They are also used to transport bulk products such as cereals and snacks. The high production speed allows the production of bulk prints in large-scale operations ([Wyatt, 1988](#)).

Inkjet printing is growing as an effective approach for enabling the production of bio-based inks and dyes in food packaging applications, addressing both ecological challenges and performance needs ([X. Luo, 2022](#)). It is a digital technology that employs small nozzles to discharge accurate droplets of liquid ink onto a substrate to produce text, images, or patterns. It functions by utilizing heat or piezoelectric mechanisms to regulate ink deposition and high-resolution prints. In thermal inkjet printing, a heating element instantly raises the temperature of the ink, creating a bubble that expands and allows a droplet into the nozzle. In piezoelectric inkjet printing, the use of an electrical current produces deformation in a crystal made of piezoelectric materials, creating stress that releases the ink droplet with no heat. This process enables accurate control of droplet dimensions, positioning, and flow, which permits high-resolution and intricate printing on various substrates ([X. Luo, 2022](#)). This non-contact method is adaptable, allowing printing on a range of materials, including paper, plastic, fabric, glass, and food. The digital aspect of inkjet printing eliminates the necessity for physical printing plates, rendering it exceptionally versatile for customized designs, quick prototyping, and limited production runs. Its capacity to merge accuracy with material adaptability has rendered it invaluable across various sectors ([Caro et al., 2016](#)).

7.4.2 Challenges in Formulation and Stability

The production and stability of bio-based inks pose distinct challenges, especially regarding advanced printing methods like inkjet and screen printing. The intrinsic characteristics of bio-based materials frequently hinder their processing and application in printing systems, necessitating a comprehensive approach in research and innovation to resolve issues concerning viscosity, surface tension, pigment dispersion, and shelf

stability. The rheological characteristics of inks are one of the crucial factors that affect the printing quality and efficiency of the system. Bio-based ink compositions consisting of natural colors, binders, and additives exhibit non-Newtonian behavior. Also, inks composed of natural polymers such as starch, cellulose, or alginates show high viscosity and shear-thinning properties and hence cannot be used in high-speed printers ([Tan et al., 2021](#)). In order to use these inks, more research has to be conducted on the formulation by integrating rheology modifiers or changing the molecular weight of these polymers, which may increase the capital cost and complexity. Another significant challenge is the maintenance of stability of the pigments. Bio-based pigments, such as carotenoids, anthocyanins, and chlorophyll, are highly susceptible to aggregation or sedimentation over time because of their hydrophobicity and various particle sizes. This causes clogging of nozzles, non-uniform color applications, and a reduction in printing quality. Surfactants are added to enhance the stability of the pigments. These additives must comply with the regulatory standards of food packaging. Additionally, natural pigments exhibit less thermal stability compared to synthetic ones; hence, they require the use of protective coatings or encapsulation methods to enhance their efficiency ([Petersen et al., 1999](#)). The drying and adhesion properties of bio-based inks are also a major concern. The drying of inks must be fast so as to maintain high-speed printing and prevent smudging, but the evaporation rate is low. For instance, water-based bio-inks require a long drying time and higher energy, making them difficult for use in industrial purposes. The surface energy variation of ink and substrate affects the adhesion of bio-inks. The adhesion of inks is improved by surface treatments such as corona discharge or plasma, but they add to the complexity and cost of production ([Nilsen-Nygaard et al., 2021](#)). The development of different printing technologies is difficult for bio-based inks as they have specific requirements such as ink viscosity, surface tension, and particle size. In the case of inkjet printing, the low-viscosity inks produce controlled droplets, whereas screen printing requires high viscosity with stable screens. The development of bio-based inks with higher

efficiency is crucial for the extension of shelf life. Many components, including natural pigments and biopolymers, are prone to changes in viscosity, color, or odor during storage. Also, exposure to light, heat, or oxygen degrades the components, and stabilizers or antioxidants must be used to extend the shelf life ([Nilsen-Nygaard et al., 2021](#)). Nanotechnology is one of the approaches to improve the efficiency of bio-based materials. For instance, cellulose nanocrystals are added to bio-based inks, which show superior mechanical and barrier properties and are highly stable compared to bio-based inks without nanomaterials ([Tan et al., 2021](#)). With recent advancements, bio-based inks can be widely utilized in food packaging, textiles, and pharmaceuticals.

7.4.3 3D Bioprinting

This is a fabrication method of 3D objects from a blueprint that is made digitally. Conventional subtractive manufacturing techniques involve the fabrication of components by eliminating the material. On the other hand, in 3D printing, the material accumulates, making it a more effective method for the production of precise and tailored designs ([Guo et al., 2019](#)). First, the computer-aided design is transferred to a readable format for the 3D printer. Typically, a file is separated into layers. Incrementally, the data is solidified and deposited by the printer. Various 3D printing technologies are being used, such as fused deposition modeling, where melting and extrusion of thermoplastic filaments take place; stereolithography, where a laser is used to polymerize liquid resins; and selective laser sintering, where a laser is used to fuse powdered materials. In bio-based inks, the 3D printing processes used are extrusion-based, vat polymerization, inkjet printing, and powder-based methods, which differ in mechanisms such as solidification or deposition of materials. Extrusion-based methods are further classified into fused deposition modeling and direct ink writing for bio-ink 3D printing. In this method, the layer-by-layer construction occurs by the controlled extrusion of bio-inks, including hydrogels and polymer composites. On the other hand, the melting and deposition are done in fused

deposition modeling. They mainly use thermoplastics such as polylactic acid ([In et al., 2021](#)). In direct ink writing, alginate and gelatin are used due to their shear-thinning properties, which allow for easy flow during the extrusion process. Vat photopolymerization methods, including stereolithography and digital light processing, employ bio-based photopolymers that solidify under ultraviolet light ([Saraswat et al., 2024](#)). These techniques provide high-resolution printing of intricate structures by the selective curing of liquid bio-inks in a layer-by-layer manner. They also comprise naturally sourced monomers or biofunctionalized acrylates engineered to replicate extracellular matrix characteristics, rendering them suitable for bioprinting and microfluidics ([Saraswat et al., 2024](#)). However, the main challenge is developing inks that are reactive to UV light without compromising biocompatibility and biodegradability. Inkjet printing is an alternative method for bio-based inks, particularly when precise droplet position is needed ([X. Luo, 2022](#)). This technique employs piezoelectric and thermal means to deposit bio-ink droplets onto the substrate. They use water-soluble polymers, cellulose, and bioactives. They are used for the production of thin films, sensors, or bioactive coatings. Powder-based methods, such as selective laser sintering and binder jetting, are less common for bio-based inks used for porous structures or complex geometry. In selective laser sintering, a laser is used to selectively fuse powdered bio-based materials, such as starch/cellulose, into solid objects, while binder jetting deposits a liquid binder onto powder layers to form a structure ([Waghmare et al., 2023](#)).

7.4.3.1 Selection of Bio-Ink for 3D Food Printing

The selection of bio-ink is essential as it influences the structural integrity, printability, and sensory attributes of foods. An appropriate bio-ink must meet the rheological characteristics, biocompatibility, and food safety regulations. Biopolymer-based bio-inks, such as alginate, pectin, and gelatin, have the capability of changing the rheological characteristics ([Outrequin et al., 2023](#)). Alginate, when crosslinked with calcium ions,

creates a durable gel network that sustains three-dimensional structures while preserving nutritional quality. Gelatin, from collagen, offers thermo-reversible gelation and improves the texture of printed foods, rendering it suitable for the use of bio-ink compositions ([Bian et al., 2024](#)). The compatibility of bio-inks with respect to food-grade components is essential. They must bind with the flavors, colors, and nutrients in the food and should not affect its nutritional and sensory properties. In the case of flavor incorporation, carbohydrate-based bio-inks such as starch and xanthan gum are highly preferred since they give no taste to the final product and also act as an emulsifier ([Cotabarren & Palla, 2022](#)). To enhance the elastic strength and mechanical properties, protein-based bio-inks such as soy and casein are used ([Wang et al., 2024](#); [Yu et al., 2022](#)).

The chemical and thermal stability of bio-inks while printing is crucial for the selection of bio-inks. Some of the bio-inks are heat-susceptible and hence require the use of stabilizers to achieve stability ([Y. Chen et al., 2021](#)). Biopolymers use composite bio-inks to exhibit enhanced stability. Also, bio-inks must be highly stable for a long period of time in order to achieve maximum efficiency. Alginate and cellulose nanofibers showed higher mechanical strength, which provides ease for the development of complex structures. Recently, the bio-ink formulation has advanced 3D food printing technology by enabling the production of customized and nutritionally stable foods with better appearance. The incorporation of functional additives, including probiotics and bioactive chemicals, into bio-inks facilitates the creation of health-enhancing foods ([Yu et al., 2022](#)). Subsequent research ought to concentrate on the advancement of intelligent bio-inks that react to environmental stimuli, such as temperature or pH, to facilitate dynamic and interactive culinary experiences.

7.4.3.2 Commercialization, Key Challenges, and Limitations of 3D-Bioprinting

The commercialization of 3D food bioprinting in food packaging is a promising technology yet difficult for commercialization ([Santoni et al.,](#)

[2022](#)). As technology advances, it encounters many constraints that restrict its widespread implementation in the food packaging sector. One of the major concerns is the modification of printers for several food types; currently, no 3D food printer exists that can print various food products at a time. Most of the existing printers still remain in the laboratory phase, and mass production is expected to take place in the next 5 to 10 years. Compared to traditional printing methods, the capital involved in 3D printing is high, making it less attractive for large-scale food packaging ([Pallottino et al., 2016](#)). The slow printing speed of 3D printers is yet another concern, limiting their use in mass production. This inefficiency constitutes an obstacle for organizations seeking to incorporate 3D printing into their packaging operations. 3D bioprinting still has lots of issues to address and is difficult for scalability and commercialization ([Santoni et al., 2022](#)). The consumer demand for the customization of foods is rapidly increasing, which will promote the use of 3D food printing ([Elemoso et al., 2020](#)). However, the lack of knowledge of consumers regarding 3D food printing at present is a major drawback with respect to commercialization ([Taghizadeh et al., 2022](#)). Also, the characteristics and safety of materials have to be evaluated in order to avoid the associated food safety risks ([Pallottino et al., 2016](#)).

7.4.4 Bio-Based Inks and Dyes for Active and Intelligent Food Packaging

Intelligent food packaging is a substantial innovation in the food packaging industry, integrating detection capabilities with sensory functions.

7.4.4.1 As an Antioxidant Agent

These bio-inks for food packaging comprise natural antioxidants that prevent oxidative degradation, extend shelf life, and are real-time indicators of the quality of food. The antioxidants are released by diffusion or stimuli-response, which is by environmental changes, oxygen levels, changes in pH, and temperature modifications ([Amani et al., 2017](#)). The main

mechanism involved is the neutralization of free radicals by the donation of electrons or metal ion chelation, which speeds up the oxidation process ([Lü et al., 2010](#)). Some of the antioxidants, such as polyphenols, flavonoids, ascorbic acid, and tocopherols, cause the stabilization of reactive oxygen species and prevent reactions that cause the degradation of protein, lipids, and other compounds ([Gulcin, 2020](#)). These bio-inks, typically chitosan, cellulose, or gelatin, function as antioxidant carriers and oxygen barriers, thereby safeguarding the food from environmental influences ([Taghizadeh et al., 2022](#)). Their efficacy is enhanced by synergistic interactions among antioxidants, such as the regenerative pairing of ascorbic acid and tocopherol, which sustains antioxidant activity over time. Nonetheless, challenges remain, such as preserving the stability of natural antioxidants during processing and storage, optimizing their controlled release for particular food systems, and ensuring adherence to food safety and regulatory standards ([Amani et al., 2017](#)). They are mainly used for high lipid and moisture foods, where oxidation is predominant. Nuts, oils, dairy products, and fish are highly prone to rancidity and off-flavor production due to the presence of unsaturated fats that undergo oxidation when they are exposed to oxygen and other environmental conditions ([Othón-Díaz et al., 2023](#)). High moisture-content foods such as fresh fruits and vegetables are susceptible to browning and discoloration of pigments ([Zhang et al., 2023](#)). These bio-inks are a promising development in active and intelligent packaging that integrates both food preservation and sustainability ([Tofanica et al., 2024](#)).

7.4.4.2 As an Antimicrobial Agent

The integration of antimicrobial agents in bio-based inks is an innovative approach for effective control of microbial infestation in food packaging. The use of ink from natural plant-based extracts and other microbial sources exhibits significant antimicrobial activity ([Halonen et al., 2020](#)). For instance, the inks with gelatin and nisin inhibit the growth of *Staphylococcus aureus* and show superior printing quality ([Dallos Ortega et](#)

[al., 2024](#)). The plant-based inks show inhibition against *Staphylococcus* and *E. coli* with preservation of their nutritional quality ([Arruda et al., 2024](#)). Silver nanoparticles can also be incorporated to enhance antimicrobial properties ([Ahmed et al., 2016](#)). These inks should have higher mechanical stability and printing quality, and the safety of the inks must be assessed ([Tambawala et al., 2022](#)).

7.4.4.3 As a pH Indicator

The pH indicators are used to assess the quality and freshness of the product. Currently, there is an increasing demand for the production of these packaging materials ([Amorim et al., 2022](#)). Various biopolymers are used as pH indicators, such as chlorophenol, bromophenol blue, and anthocyanin. These pigments change color according to the change in the hydrogen ion concentration ([Păușescu et al., 2022](#)). For example, anthocyanins display a broad spectrum of color variations with elevated alkalinity due to the reduction of hydronium ions, which modifies the molecular structure. This feature can be employed in the construction of group indicators that monitor pH levels in packaged food, including indicators for food spoilage, CO₂ levels, and ripeness ([Martins et al., 2022](#)). Advanced formulations additionally integrate colorimetric indications that visually denote alterations in food freshness, typically via variations in pH-sensitive dyes upon exposure to spoilage gases such as carbon dioxide or ammonia ([Martins et al., 2022](#)). pH-sensitive inks are predominantly used in meat packaging applications. One of the recent innovations is the development of nano-inks with anthocyanin extracted from saffron petals and curcumin into chitin to monitor the freshness of shrimp with pH sensitivity. The change in pH is used to determine the extent of chemical and microbial reactions, which determines the shelf life of shrimp ([Mehrzaad et al., 2024b](#)). The 3D-printed film with alginate, gelatin, and nanocellulose, in addition to its pH-sensitive properties, also shows superior mechanical properties, durability, and flexibility. They change color due to differences in pH from 2 to 13 and act as a freshness indicator in packaged meat and

fish ([Popoola et al., 2024](#)). Also, a study incorporated anthocyanin and curcumin into edible inks to measure the degree of freshness of pork. The changes in the color of ink with pH changes and the extent of spoilage are positively correlated ([Hu et al., 2025](#)) ([Table 7.1](#)).

TABLE 7.1 Different Types of Dyes and Inks, Their Sources, Properties, and Their Food Packaging Applications 

<i>TYPES</i>	<i>SOURCES</i>	<i>COLOR</i>	<i>PROPERTIES</i>	<i>APPLICATIONS</i>
Plant Based				
Anthocyanins	Grapes, berries, red cabbage	Red, purple, and blue	Antimicrobial, antioxidant, pH sensitive, freshness indicator	Meat, fish, dairy products, bakery products, beverages
Carotenoids	Carrots, tomatoes, saffron	Yellow, orange, red	Antioxidant, UV-protection	Juices, dairy products, bakery products
Chlorophyll	Green leafy vegetables	Green	Antimicrobial, oxygen scavenger	Fruits, vegetables, snacks, bakery
Betalains	Beetroot	Red, yellow	pH sensitive, antioxidant	Meat, dairy, seafood, bakery
Animal Based				
Carminic acid	Cochineal insect	Red to crimson	pH sensitive	Meat, fish
Tyrian purple	Snails	Deep purple to violet	UV protection	Dairy products such as cheese and beverages
Microbial Based				
Carotenoids	<i>Bradyrhizobium spp</i>	Orange to deep	Antioxidant	Bakery, dairy products such as

TYPES	SOURCES	COLOR	PROPERTIES	APPLICATIONS
		pink		cheese, butter, yogurt
Violacein	<i>Chromobacterium violaceum</i>	Purple	Antimicrobial, antioxidant	Meat, seafood, dairy products, beverages
Riboflavin	Fungi	Yellow	Antioxidant	Milk, bakery
Phycocyanin	Cyanobacteria-Spirulina	Blue	Antioxidant, pH sensitive	Dairy, meat, beverages

References: ([Tiwari, 2022](#); [Thakur et al., 2023](#); [Puttipan & Khankaew, 2023](#); [Szadkowski & Marzec, 2024](#); [Nilsen-Nygaard et al., 2021](#); [Pavlović et al., 2022](#); [Hakim et al., 2024](#); [Bian et al., 2024](#)).

7.5 APPLICATIONS OF BIO-BASED INKS AND DYES IN FOOD PACKAGING

7.5.1 Meat Packaging

The emission of greenhouse gases like carbon dioxide from meat and poultry products is 13–18% greater than that of fruits and vegetables. Therefore, there is a need to minimize food waste caused by animal products by using a sustainable and cost-effective packaging system ([Versino et al., 2023](#)).

7.5.1.1 Specific Requirements for Inks and Dyes in Meat

There are certain specific requirements, including less solvent retention, stability in moist environments, fluctuations in temperature, and low migration rate, for the usage of inks and dyes in meat packaging systems. The inks and dyes must follow the EU regulatory standards, such as EU

10/2011, EC 1935/2004, and ISO 22000, to ensure the safety and integrity of the food product. Also, according to USFDA guidelines, the substances that are added to packaging material should not pose a serious threat or harm, and specific migration limits should be followed. The inks or dyes should be dissolved in nontoxic solvents and should be applied to intermediate layers of the food packaging to avoid direct contact with the food product. The inks should be stable during processing and storage and should not interfere with the natural appearance of the myoglobin derivatives in the meat products. The inks should be biodegradable, should have low volatile organic emissions, should provide essential information, and must be resistant to fading or refrigeration ([Luo et al., 2022](#); [Versino et al., 2023](#)). Methyl red and bromocresol dyes are used as pH indicators in meat packaging. These indicators are highly responsive in the pH range of 5.61–6.23, where spoilage reactions in meat occur. The color of the sensor changes from red to yellow and then from purple to red as the spoilage reactions occur ([Anil, 2017](#)). The bromocresol purple dye infused with agarose gel is used as a pH-sensitive indicator in chickens. Also, bromocresol green, when coated on LDPE film, is used in chicken breasts, which change in color according to the changes in pH ([Lee et al., 2019](#)). The starch nanoparticles with bromocresol green effectively monitor the spoilage of meat and its products ([Fatehi et al., 2024](#)). Composite films made with polyvinyl alcohol, starch, and glycerol, loaded with curcumin and anthocyanin, have proven to be the best indicator of fish spoilage ([Chen et al., 2020](#)). Potato starch film loaded with cyanidin red onion extract gives a distinct color change, which varies according to the pH, which is used for detecting spoilage reactions in meat. The volatile amines produced due to the spoilage of meat rapidly change the color of the film from pink to dark green ([Boccalon et al., 2022](#)).

7.5.2 Packaging of Dairy-Based Products

Food packaging materials used for the packaging of dairy products must protect the product from dirt, microorganisms, light, and varying

temperature conditions. Various inks and dyes used in dairy-based packaging materials should primarily ensure the safety of the product, enhance shelf life, and should be able to communicate with the customer.

7.5.2.1 Case Studies

Intelligent packaging of dairy products involves the usage of thermochromic dyes, oxygen-indicator inks, and conductive inks ([Rejeesh & Anto, 2023](#)). Thermochromic inks like the AIPE-active cationic Ir (III) complex are one of the common temperature-sensitive dyes used in the dairy industry. These are a mixture of two inks using ethanol and water as solvents. The dyes loaded into the film changed their color according to variation in temperature conditions from yellow to yellowish green and from yellowish green to orange at temperature conditions of 180°C to 220°C ([Thamrin et al., 2022](#)). These dyes are used in sterilized milk and show higher efficiency. The shelf life of dairy products can be monitored via temperature-sensitive dyes developed with enzymes such as polyphenol oxidase and lipase ([Mirza Alizadeh et al., 2022](#)). Films developed from anthocyanins extracted from red cabbage are used to detect cheese quality. The film color is positively correlated with the microbial population ([Bandyopadhyay et al., 2020](#)). Oxygen indicators are used to monitor the quality of milk and other dairy products. Methylene blue is a dye that changes its color upon oxidation and reduction reactions. Many luminescent materials are placed in dairy packaging films like silicone rubber and polymers. Tris(4,7-diphenyl-1,10-phenanthroline) ruthenium(II) perchlorate is a common redox dye-based indicator used in food packaging ([Dobrucka, 2013](#)). Conductive inks are made of metal nanoparticles or nanosheets dispersed into a solution containing amphiphilic polymers. Conductive inks work on the principle based on the interplay of particle concentration, innovative material combinations, and quantum effects. Conductive inks containing silver-copper nanoplatelets were synthesized, and these showed promising applications in intelligent packaging. Nanotubes made of zinc oxide and zinc sulfide were used as biosensors for the detection of glucose.

These conductive inks, which are embedded in the packaging material, can also be used to collect data on the purchasing habits of the consumer ([Krishna et al., 2023](#)).

7.5.3 Fruit and Vegetable Packaging

Smart packaging of fruits and vegetables is used to track the ripeness and spoilage of fruits and detect microbial contamination or the presence of harmful gases like ethylene.

7.5.3.1 Considerations for Fresh Produce Packaging

Inks and dyes used in the intelligent packaging of fruits and vegetables should be able to detect exposure to different temperature conditions, provide signals regarding ripeness and spoilage, and monitor changes in pH that occur during spoilage ([Bisht & Gaikwad, 2025](#); [Hakim et al., 2024](#)). Inks should be compatible with the packing material and should not interact with the membrane of the fruit or the vegetable. The indicators should be designed in such a way that they are specific to a fruit or vegetable or the commodities belonging to the same family. The inks and dyes should maintain their functionality over the expected shelf life of the fruits. The type, method, and concentration of the inks should adhere to the food packaging regulations ([Liu et al., 2025](#); [Luo et al., 2022](#); [Hakim et al., 2024](#)).

7.5.3.2 Bio-Based Inks and Dyes for Shelf-Life Extension

Bio-based inks and dyes are naturally extracted from plant sources, microorganisms, or food products. Various bio-based dyes are derived from natural sources like curcumin from turmeric, betalains from beetroot, phycocyanin from spirulina, and anthocyanins from berries and purple sweet potatoes. The inks used for printing contain a colorant, which is a pigment, a resin, and solvents used to dissolve various components and additives like plasticizers, wax, chelating agents, humectants, and

surfactants. Bio-based inks and dyes are safer alternatives to synthetic dyes as they are environment-friendly and biodegradable ([Hakim et al., 2024](#)). The extraction of certain metabolites like L-lactic acid, D-lactate, acetic acid, and volatile amines and their incorporation in food packaging are used to sense changes in pH. Natural pigments like flavonoids and anthocyanins are found in most fruits and vegetables and can be used as pH-sensing labels in active food packaging. In dates, anthocyanin in the PVA matrix is used as an indicator to measure the spoilage of fruits. Also, bromophenol blue and bacterial cellulose indicate the degree of ripeness in mangoes ([Q. Luo et al., 2023](#)). The combination of bromothymol blue and methyl red in a 2:3 ratio can be used as a freshness indicator when bell peppers are stored at 7 °C. Phycocyanin-loaded polylactic acid/polyethylene oxide nanofibers are used as pH sensors in active food packaging to indicate different stages of maturity and ethylene production ([Forghani et al., 2023](#)).

7.5.4 Bakery and Confectionery Packaging

The packaging materials used for baking and confectionery packaging are embedded with smart technologies to enhance aesthetics, product visibility, product quality, safety, and consumer experience.

7.5.4.1 Functional Roles of Inks and Dyes in Bakery and Confectionery Packaging

The major function of naturally extracted plant inks and dyes in the field of baking and confectionery packaging is to enhance the appeal of the packaging materials by using attractive designs and logos and enhancing brand identity. It also provides details on nutritional composition, regulatory compliance, and batch numbers. Certain inks and dyes highlight any tampering in the packaging material and are also temperature-sensitive in nature. Pigments extracted from *Terminalia catappa* are used as ecofriendly inks in packaging materials. The inks are suitable for the direct printing of bread, cookies, crackers, and other products. The water-based edible inks are used in toffees, jelly beans, and chocolates, allowing high-resolution

images during printing ([Hakim et al., 2024](#)). Inks composed of food-grade materials can be used to print on different bakery products like cakes, cookies, and breads. The food industry uses edible inks for the customization of cakes, chocolates, and pastries. The most common colorings that are extracted from plant sources include Tyrian purple, indigo, turmeric, weld, safflower, logwood, black walnut, bloodroot, sumac, red cabbage, annatto, and osage orange ([Hakim et al., 2024](#)). A commercial time temperature indicator known as a smart dot changes its color from green to red when exposed to a temperature change. This indicator is mainly used for bakery and frozen food products. Another time temperature indicator named 3MTM MonitorMark is also used in the intelligent packaging of bakery products, which is based on the principle of diffusion of colored dye-based ester into viscous material matrix. The main working principle behind this dye is melting and diffusion. When the temperature exceeds the critical temperature, the substance melts and causes a blue color ([Kalpana et al., 2019](#)).

7.6 CHALLENGES AND FUTURE PROSPECTS

7.6.1 Current Challenges

7.6.1.1 Technical, Economic, and Regulatory Hurdles

The intelligent packaging of food products has immense potential in the field of active food packaging to maintain quality and communicate freshness. A major concern regarding the use of inks and dyes is regulatory compliance. The inks should be safe and non-toxic, and the migration of these inks and dyes should not exceed permissible limits. The use of dyes extracted from natural sources may contain allergens. The dyes extracted from plant sources may be susceptible to environmental conditions, leading to their degradation. The dyes must be compatible with various polymeric

materials and various processing parameters and conditions. Natural bio-based inks and dyes are far more expensive than synthetic dyes. While there are many environmental concerns relating to the use of synthetic dyes, natural dyes also need to be extracted in sufficient quantities without disturbing biodiversity. Consumer awareness about the usage of bio-based inks is important ([Versino et al., 2023](#); [Wang et al., 2024](#); [Luo, 2022](#); [Tambawala et al., 2022](#)).

7.6.2 Future Trends and Innovations

7.6.2.1 Emerging Technologies in Bio-Based Inks and Dyes

Various emerging technologies like nanoencapsulation, nanofabrication of nanocomposites, and engineering microorganisms and algal cultures are used to produce dyes and pigments. Extraction of dyes like carotenoids and chlorophylls can be done using supercritical fluid extraction, enzymatic extraction, and ultrasound-assisted extraction. Sustainable manufacturing processes like extraction from waste, anthocyanin from berry peels, and low-carbon footprint production are used for the manufacture of bio-inks. Customization of packaging designs was formulated using 3D printing and advanced inkjet printing technologies to enable precise deposition of bio-inks. Machine learning and artificial intelligence can be used in dye formulations and in identifying new inks and pigments from natural sources ([Hakim et al., 2024](#); [Ozcan & Arman Kandirmaz, 2020](#); [Saraswat et al., 2024](#)).

7.6.2.2 Potential Impact on the Food Packaging Industry

The usage of bio-based inks and dyes is a significant step toward environmental sustainability. This reduces the heavy dependence on synthetic and petroleum-based dyes. Usage of bio-based inks and dyes has a significant impact on environmental sustainability as they are renewable and biodegradable. Natural dyes like annatto are non-toxic and safe, which can also be used in direct contact with food. Governments and industries are

encouraging the use of food-grade inks and dyes by coming up with regulations and providing incentives for sustainable practices. Natural dyes such as carotenoids also protect the materials from UV radiation and act as an indicator in smart packaging. The main drawback is the cost and durability of these dyes, which affects their usage in food industries ([Versino et al., 2023](#); [Bisht & Gaikwad, 2025](#)).

7.7 CONCLUSION

Bio-based inks and dyes in food packaging offer a sustainable option in food packaging. The increased environmental effects and health concerns with the use of conventional inks and dyes have resulted in the utilization of bio-based inks and dyes with highly biodegradable nature. Also, carbon footprints are reduced after the use of these inks, and the concerns related to the chemical migration from packaging material are tackled. The incorporation of bio-based inks and colors in food packaging signifies a substantial advancement in sustainable industry practices. Utilizing renewable resources and advanced production techniques, these materials promote environmental conservation and improve food safety. Ongoing research aims to address current issues, indicating a promising future for bio-based inks and fostering a more sustainable packaging environment that meets consumer preferences and regulatory standards. Since they are derived from natural sources such as plants and microbes, they not only reduce the environmental impact but also improve the functionality of the packaging material by acting as antimicrobial, antioxidant, and pH-sensitive components in the packaging of fruits, vegetables, dairy, meat, bakery, and confectionery products. With the rise in 3D printing, bio-based inks and dyes enable customized designs with the maintenance of a high degree of precision. Despite the benefits, there are still a few challenges with respect to their stability and production costs, which are major concerns in the commercialization of these inks. More research on encapsulation

technologies and the formulation of printing inks compatible with 3D printing will help in overcoming the hurdles and widespread use of bio-based packaging.

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Sustainable Biomaterials for Fresh Meat and Meat Products

8

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8.1 INTRODUCTION

Since the 1950s, global plastics production has surged, reaching an estimated 450 million metric tons annually in recent years. Despite their utility, plastics generate significant environmental concerns, with over 340 million tons of plastic waste produced yearly, nearly 46% from packaging ([Wu et al., 2021](#)). Petroleum-based packaging, known for its durability and protective properties, is widely used in advanced packaging techniques like vacuum and modified atmosphere packaging ([Trinh et al., 2023](#)). However, growing environmental and resource depletion concerns have increased interest in sustainable alternatives ([Singh et al., 2022](#)). Biopolymers, derived from natural resources such as pectin, starch, carboxymethyl cellulose, gelatin, chitosan, and alginate, offer strong, durable, and often edible packaging solutions. This promotes innovation in biodegradable and edible food packaging for items like fruits, vegetables, and especially meat

([Poosarla et al., 2024](#); [Ramadoss et al., 2025](#); [Sani et al., 2023](#); [Tian et al., 2024](#)).

Meat is a highly perishable and staple food product with a limited shelf life. It is a nutritionally rich product of proteins, vitamins, and minerals, influenced by oxidation, enzymatic activity, bacterial growth, and environmental conditions. Among these, temperature and humidity during storage are particularly critical, as they directly affect meat quality and spoilage rates ([Amit et al., 2017](#)). Processing and preservation techniques, including packaging and storage conditions, are vital for meat preservation. Hence, meat industries pay critical attention to the shelf life extension of meat ([Cenci-Goga et al., 2020b](#)).

Fresh meat is particularly susceptible to microbial growth due to its high water content and nutrient density, creating an ideal environment for pathogens and spoilage microorganisms. Lipid oxidation, a chemical reaction involving fats, leads to off-flavors, discoloration, and textural changes, reducing meat's appeal and shelf life. Inadequate storage conditions and ineffective barriers against oxygen and contaminants accelerate these spoilage mechanisms ([Karanth et al., 2023](#)). Spoiled meat poses serious health risks, underlining the importance of preserving its quality and safety ([Vasilopoulos et al., 2015](#)). Additionally, the economic implications of meat spoilage are significant, contributing to food waste and revenue losses for producers and retailers ([Ghosh et al., 2016](#)).

Intelligent and active packaging solutions have emerged as an important tool in meat preservation. Active packaging incorporates antimicrobial agents and oxygen scavengers, which actively combat microbial growth and oxidative processes, thus significantly extending shelf life. These innovative materials preserve meat's sensory and nutritional qualities and reduce the risk of contamination. On the other hand, intelligent packaging offers real-time monitoring of freshness, using indicators to track factors such as spoilage or temperature fluctuations, enabling consumers and retailers to minimize food waste ([Fang et al., 2017](#)). This chapter provides in-depth knowledge about traditional packaging materials, emerging sustainable

biomaterials for meat preservation, their environmental and economic benefits, and the future trends for sustainable meat packaging.

8.2 IMPACT OF DETERIORATION ON MEAT QUALITY

Meat and meat products are a nutritionally rich source as they contain carbohydrates (0.5–1.5 %), fat (1–13%), protein (16–22%), water (75%), minerals, and vitamins, making them highly perishable. The nutritional composition of different animal meats has been mentioned in [Table 8.1](#). Meat has a water activity (a_w) > 0.95, facilitating the growth of spoilage-causing microorganisms. The quality of meat and meat products can be determined using flavor, odor, color, and texture. Several extrinsic and intrinsic factors are the main reasons for meat spoilage, such as breed, age, improper handling of livestock, processing conditions, pH, hygienic conditions, lipid oxidation, and storage temperature. Discoloration of meat is directly related to spoilage. The preservation of meat is possible through the addition of nitrites and salts. Several packaging techniques, like vacuum and modified atmosphere packaging, are used ([Dave & Ghaly, 2011](#); [Wongphan et al., 2024](#)).

Meat contains myoglobin, a red pigment and complex hemoprotein responsible for its coloration. The meat color is influenced by redox reactions involving the iron atom in the heme group. Oxidation converts ferrous iron (Fe^{2+}) to its ferric form (Fe^{3+}), forming metmyoglobin and a brown hue. Conversely, reduction transforms ferric iron back to ferrous, producing deoxymyoglobin, characterized by a purple color. These transformations between deoxymyoglobin and metmyoglobin are central to meat's visual quality and perception. The rate of lipid oxidation depends on the pH, microbial growth, temperature, and meat activity. The reduction process is reversible and depends on pH, meat activity, oxygen content, temperature, and bacterial content. The conversion of myoglobin to

metmyoglobin and deoxymyoglobin has been represented in [Figure 8.1](#) ([Ordway & Garry, 2004](#); [Wongphan et al., 2024](#)).

TABLE 8.1 Nutritional Value of Raw Meat Products ↵

<i>MEAT</i>	<i>ENERGY (KCAL)</i>	<i>PROTEIN (G)</i>	<i>FAT (G)</i>	<i>SATURATED FAT (G)</i>	<i>REFERENCE</i>
Chicken breast, skinless	108	24.1	1.2	0.3	(Pereira & Vicente, 2013)
Chicken breast	120	22.5	2.62	0.56	(Bohrer, 2017)
Beef, steak cuts	122	21	4.3	1.8	(Pereira & Vicente, 2013)
Beef, strip loin	228	20.61	15.49	6.25	(Bohrer, 2017)
Beef, calf, loin	148	19.9	7.6	3.2	(Pereira & Vicente, 2013)
Pork, chop	355	17.3	31.8	10.9	(Pereira & Vicente, 2013)
Pork, leg	152	21	7.5	2.6	(Pereira & Vicente, 2013)
Pork, loin	134	21.9	4.9	1.7	(Bohrer, 2017)
Duck meat, skinless	130	19.4	6.6	1.8	(Pereira & Vicente, 2013)
Turkey, breast	106	21.89	7.02	1.91	(Bohrer, 2017)
Turkey, skinless	137	20.5	6.1	2	(Pereira & Vicente, 2013)
Mutton, chop, or	124	19.7	5	2.2	(Pereira & Vicente, 2013)

<i>MEAT</i>	<i>ENERGY (KCAL)</i>	<i>PROTEIN (G)</i>	<i>FAT (G)</i>	<i>SATURATED FAT (G)</i>	<i>REFERENCE</i>
meat					
Salmon	142	19.84	6.34	0.98	(Bohrer, 2017)
Tilapia	96	20.08	1.7	0.58	(Bohrer, 2017)
Tuna	109	24.4	0.49	0.17	(Bohrer, 2017)



FIGURE 8.1 Transformation of myoglobin into metmyoglobin and deoxymyoglobin. [↗](#)

8.3 FACTORS AFFECTING MEAT SPOILAGE

8.3.1 Endogenous Enzymes

The active endogenous enzyme breaks down the tissues in meat after the animal's death. The main endogenous protease system, the calpain system, consists of m-calpain and μ -calpain. The tenderness of the meat increases after slaughter due to the activation of these components in meats like chicken breast and sheep meat ([Yan et al., 2018](#); [Zhao et al., 2018](#)). The lysosomal and calpain systems primarily mediate protein degradation in skeletal muscle. Among lysosomal enzymes, cathepsins B, D, and L significantly influence muscle texture by contributing to the breakdown of muscle structure ([Wang et al., 2013](#)). Additionally, key endogenous enzyme caspases exhibit increased activity during post-slaughter ([Yayuan et al., 2022](#)). Following slaughter, muscle pH declines, and the activity of

endogenous enzymes diminishes, particularly when the pH approaches 5. This reduction in enzymatic activity indicates that their contribution to post-slaughter changes is relatively minor compared to the effects of microbial spoilage ([Hernández et al., 2018](#)).

8.3.2 Microorganisms

Meat's shelf life is significantly influenced by spoilage pathogens and bacteria present on its external surfaces ([Rahman et al., 2023](#)). Spoilage becomes evident when microorganisms deplete the meat's lactate and glucose and metabolize protein ([Doulgeraki et al., 2012](#)). Microbes like *Thermococcus* sp., *Pseudomonas* sp., and *Lactobacillus* sp. metabolize available substrates, producing volatile fatty acids, ketones, ethyl esters, ammonia, aldehydes, sulfur compounds, and organic acids. These byproducts lead to discoloration and off-flavors, which render the meat inedible during storage ([Saenz-García et al., 2020](#); [Yushina et al., 2019](#)). Lactic acid bacteria (LAB) in meat produce ethanol, acetic acid, lactic acid, and CO₂ and are either obligate heterofermentative or facultative heterofermentative, generating lactate from glucose. Under aerobic storage conditions with limited glucose, many spoilage-associated LAB oxidize pyruvate or lactic acid to acetic acid, which imparts a strong vinegar flavor, negatively affecting the meat's sensory quality ([Cenci-Goga et al., 2020b](#); [Mansur et al., 2019](#)). Moreover, LAB utilizes amino acids and produces biogenic amines, which may cause health risks to customers ([Schirone et al., 2022](#)). *Pseudomonas aeruginosa* has been shown to produce considerable volumes of methyl acetate and ethyl acetate under freezing and aerobic conditions in meat sauce, further contributing to spoilage ([Stanborough et al., 2018](#)).

Effector proteins are molecules, typically produced by pathogens, that interact with host cells to modulate their functions, often to the pathogen's advantage. These proteins are secreted by various pathogens, including bacteria, fungi, viruses, and parasites, through specialized secretion systems. They also play a critical role in hydrolyzing invasive, pathogenic,

and biologically active proteins, including extracellular proteins secreted by bacteria and structural proteins involved in secretion systems. Examples of effector proteins include HasA of *Serratia marcescens*, HlyA of *Escherichia coli*, and RtxA of *Vibrio cholerae* ([Thomas et al., 2014](#)). Enzymes secreted by microorganisms like *S. marcescens* and *Pseudomonas aeruginosa* possessing lipase or protease activity significantly degrade food's physical and chemical properties. This enzymatic activity adversely affects animal-derived meat's functional and sensory quality ([Zhang et al., 2019](#)). Both microbial extracellular enzymes and endogenous enzymes in meat drive biochemical reactions that impact lipids, proteins, and carbohydrates. These reactions can change the meat's quality, texture, and flavor, diminishing sensory appeal and product acceptability ([Landeta et al., 2013](#)).

8.3.3 Oxidation

Oxidation is a significant challenge in storing meat, significantly impacting its quality, flavor, and consumer acceptability. Oxidation of polyunsaturated fatty acids produces lipid hydroperoxides, accelerating meat deterioration ([Martini et al., 2021](#)). This process can be catalyzed by metal ions, reactive oxygen species (ROS), and reactive nitrogen species (RNS). Unsaturated fatty acids indirectly interact with oxygen during oxidation, forming highly reactive species like hydroxyl radicals, hydrogen peroxide, and superoxide anion radicals ([Hadidi et al., 2022](#)). Hydroxyl radicals, the most reactive form of ROS, are a primary driver of oxidative damage to lipids and proteins. Heat treatments further exacerbate this issue by weakening the muscle's natural antioxidant defenses, making proteins more susceptible to oxidative damage ([Domínguez et al., 2021](#); [Lund et al., 2011](#)). Meat spoilage is often accompanied by the release of volatile components due to the metabolic breakdown of proteins and non-protein nitrogenous components, leading to a freshness loss. Key microbial markers of spoilage include volatile amines like dimethylamine, trimethylamine, and ammonia ([Don et al., 2018](#)). Alongside unpleasant odors caused by excessive lipid and protein oxidation, it contributes to off-flavors, textural degradation,

discoloration, and nutritional loss. Therefore, minimizing free radical-mediated lipid and protein oxidation during meat processing and production is critical to preserving its sensory and quality attributes ([Chen et al., 2023](#); [Xie et al., 2023](#)).

8.4 NON-BIODEGRADABLE PACKAGING IN MEAT PRESERVATION

Plastics of 7,800 million tons were produced between 1950 and 2015, whereas approximately 3,900 million tons were produced between 2002 and 2015. Plastics are used in several sectors of the food industry, including preservation, storage, protection, and transport ([Kedzierski et al., 2020](#)). Commonly used petroleum-based polymers in the food industry are polystyrene (PS), polypropylene (PP), polyvinylidene chloride (PVDC), polycarbonate (PC), polyethylene terephthalate (PET), and high and low-density polyethylene (HDPE and LDPE, respectively). PP and PE are primarily used in single-use plastics. Polycyclopentadiene and polybutene (PB) have recently become popular in the packaging industry ([Dey et al., 2021](#)). Most of these polymers are flexible, tough, and can form thin layers. These polymers protect against microorganisms, water vapor, and oxygen. Migration of plasticizers into roasted chicken meat from the plastic packaging of food was observed ([Guerreiro et al., 2018](#)). Several studies also show the alarming release of plastic nanoparticles and microplastics into food, contaminating it ([Fasihnia et al., 2020](#); [Kaseke et al., 2023](#)). These microplastics are 5 mm in size, and studies suggest that humans consume these particles. Several food sources contain these microplastics, including fish, salt, seafood, beer, and water bottles ([Kedzierski et al., 2020](#)). Microplastics migrate faster when an oily stimulant is used, leading to hydrophobic interactions. As meat products are fatty, the microplastics tend to migrate easily ([Katsara et al., 2022](#)).

8.5 BIODEGRADABLE FILMS AND COATINGS FOR MEAT PRODUCTS

Biodegradable polymers are produced from renewable resources with low carbon emissions. Natural, sustainable resources consisting of agricultural and food by-products are used. They are non-toxic, possess good barrier and mechanical properties, and are compostable and biodegradable. Hence, they are suitable for food and agriculture applications ([Khodaei et al., 2021](#)). Biodegradable polymers and coatings are mainly of three types such as synthetic polymers like polycaprolactone (PCL) and polylactic acid (PLA); natural biodegradable and renewable sources like polysaccharides (chitosan, alginate, cellulose, and starch), proteins (casein, gelatin, and soy), and lipids (oils and waxes); and polymers obtained from natural biosynthesis due to microbial stress such as polyhydroxyalkanoates (PHA) ([Gagaoua et al., 2021](#)). [Figure 8.2](#) shows several biodegradable polymers and coatings that are commonly used in the meat industry.

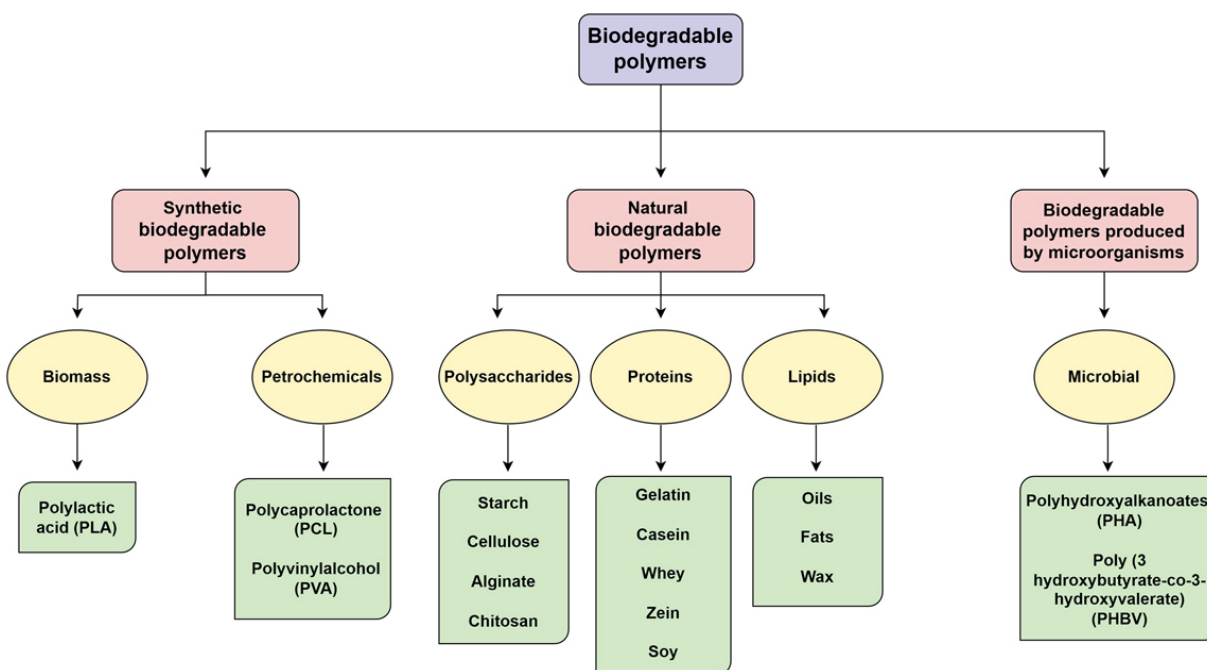


FIGURE 8.2 Classification of biodegradable polymers. [↗](#)

8.5.1 Polylactic Acid (PLA)

PLA is a renewable, biodegradable thermoplastic known as one of the most commercially used polymers. It involves converting carbohydrate-rich sources (usually corn) into dextrose, which is then fermented to produce lactic acid. Lactic acid production involves converting carbohydrate-rich sources like corn into dextrose. The dextrose is then fermented by *Lactobacillus* sp. bacteria under controlled conditions, converting it into lactic acid. The final product is purified for food, bioplastics, and pharmaceuticals, offering a sustainable approach to utilizing renewable resources. PLA offers tensile strength comparable to many conventional polymers, making it a potential alternative for various industrial and commercial uses. It provides appropriate strength, compostability, and biodegradability for the meat packaging. They act as odor and flavor barriers, can be sealed at low temperatures, and are oil-resistant. This prevents the meat from absorbing external flavors or odors. It is a low-cost polymer that demonstrates desirable light transmission ([Panseri et al., 2018](#); [Wang et al., 2022](#)). PLA is hydrophobic as it has a steric shielding effect due to the methyl groups. It is transparent and rigid, has a tensile strength (TS) of 45–70 MPa, elongation at break (EAB) of 85–105% with a Tg of 53 °C, and a melting point of 170–180 °C ([Taib et al., 2023](#)). They can preserve the red color of the meat. They have moderate barriers to aroma and water vapor and low barriers to oxygen, which enhances the shelf life of meat and reduces the pH change, dehydration, and oxidation, hence promoting food quality and safety ([Hernández-García et al., 2022](#)). Several studies such as when PLA film composites in combination with nanochitosan and antimicrobial agents such as *Polylophium involucreatum* essential oil (EO) applied on minced lamb, which improves the sensory properties and extends the shelf life for 11 days ([Bafroee et al., 2020](#)), PLA coated with chitosan or chitosan/sodium alginate and 2% rosemary EO on minced chicken breast displayed reduction of the content of malondialdehyde by 50% and better retention of color till by the end of day 21 ([Fiore et al., 2021](#)), PLA in combination with 6% lemon extract on beef

meat showed inhibition of lipid oxidation for six days and total microbial growth till day 8 of shelf life analysis ([Andrade et al., 2023](#)), and PLA in combination with 1.5% *Origanum majorana* EO and 1% zinc oxide (ZnO) nanoparticles on ground meat improved the sensory property and enhanced the shelf life ([Negahdari et al., 2021](#)) ([Table 8.2](#)).

8.5.2 Polycaprolactone (PCL)

Poly- ϵ -caprolactone is a strong and comparatively inexpensive cyclic monomer. It is a semi-crystalline linear polymer formed by carrying out the ring-opening polymerization of ϵ -caprolactone using a tin octoate catalyst. It is a hydrophobic, biodegradable, and biocompatible polymer. It is an ideal substitute for conventional petroleum-based polymers as it provides good mechanical properties. It has 23 MPa TS, 700% EAB, -60°C Tg, and a 60 °C melting point, making it suitable for meat packaging. Its biodegradation rate can be increased when combined with other copolymers ([Lyu et al., 2019](#); [Zhu et al., 2024](#)). PCL, when used for packing meat, also enhances the oxygen barrier property, and when used in combination with antimicrobial agents, PCL exhibits good antimicrobial properties ([Correa et al., 2017](#); [Dong et al., 2017](#)). Antimicrobial agents such as carbon dot nanoparticles extracted from Zedo gum on beef extend the shelf life for more than five days, preventing bacterial spoilage and oxidation ([Ahmadi et al., 2024b](#)); nisin extends the shelf life from 7 to 28 days, and it exerts effective antimicrobial activity against *Lactobacillus plantarum* inoculated on ham ([Correa et al., 2017](#)); silver nanoparticles display low peroxide value, thiobarbituric acid reaction, total volatile basic nitrogen (TVBN), and pH; preserve the quality; enhance the shelf life; prevent spoilage; and food-borne microorganisms of Tilapia meat ([Ahmadi et al., 2024a](#)) ([Table 8.2](#)).

8.5.3 Starch

Starch is a carbohydrate and natural polymer available in granular form in the endosperm layer of unripe fruits, roots, legumes, and other plant storage parts. The starch-based films are tasteless, colorless, low-cost, inexpensive,

biodegradable, and readily available. The two different forms of starch molecules are amylose (the simplest form of linear polymer) and amylopectin (a complex structure) ([Putri et al., 2023](#)). The TS of several starches that are available are tapioca starch (0.78 MPa), oat starch (0.36 MPa), potato starch (3.05 MPa) ([Żółek-Tryznowska & Kałuża, 2021](#)), and cassava starch (4.21–6.95 MPa) ([Costa et al., 2022](#)). Due to their good mechanical properties, starch can be a good alternative to plastics, and they have various applications in the food packaging industry, like bread, fruits, snacks, vegetables, and meat packaging ([Bangar et al., 2021](#)). Many studies have been done on meat packaging, mainly using starch, where the tenderness of the meat has been improved by edible starch films, which are incorporated with papain ([Zhao et al., 2019](#)), cassava starch blended with poly (butylene adipate terephthalate) increases the oxygen barrier properties, and nitrites stabilize and improve the meat color ([Leelaphiwat et al., 2022](#)) ([Table 8.2](#)).

TABLE 8.2 Biodegradable Polymers Used in the Preservation of Meat [!\[\]\(74af671ca58b59936a1e6f13fb8f5010_img.jpg\)](#)

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATION
1	PLA	-	<i>Origanum majorana</i> EO, zinc oxide nanoparticles	Ground meat	Extends shelf life, improves packaging material chemical properties
2	PLA	Sodium caseinate	<i>Rosemary officinalis</i> EO, chitosan	Chicken breast meat	Preservation potential

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATION
					pack
3	PLA	-	<i>Polylophium involucreatum</i> EO, nanochitosan	Minced lamb	In ox st s prop exte
4	PCL	Hairy cellulose nanocrystals	Silver nanoparticles	Tilapia fish	Rei anti and a pro ext shel prese
5	PCL	PHB, organo-clay	Nisin	Ham	E ag pl inoc h ext sl
6	PHB	PLA	Fennel oil	Oysters	R aer ar bacte disp

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATION
					total basis
7	Cassava thermoplastic starch	Linear low-density polyethylene (LLDPE)	Green tea	Bacon	Remains good for 1 month in refrigerator
8	Potato starch	-	Green tea extract/butylated hydroxy toluene	Fresh beef	Decrease in microbe formation during storage
9	Cassava thermoplastic starch	Poly (butylene adipate terephthalate)	Nisin	Pork collar	Retention of quality by slowing lipid oxidation
10	Carboxymethyl cellulose (CMC)	Polyvinyl alcohol	Clove oil	Ground chicken meat	Improvement in shelf life of meat in refrigerator
11	Bacterial cellulose	Polypyrrole	Zinc oxide	Chicken thigh	Decrease in microbe content, increase in shelf life,

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATION
					the r pro in anti and a a
12	Alginate	Hydroalcoholic extract	Pineapple peel extract	Beef meat	I mesc a micro main and r oxida stora
13	Sodium alginate	-	<i>Synzygium aromaticum</i> and <i>Aloysia citriodora</i> EOs	Chicken breast	Incre life red nu micro
14	Sodium alginate	-	Titanium dioxide, cumin EO	Fresh beef	Red ox m sp in sensc and
15	Chitosan	Sodium alginate	Silver nanoparticles, lemongrass oil	Boneless goat meat	R m g enha

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATIONS
					li er anti a
16	Carboxymethyl chitosan	Zinc alginate	Zinc alginate	Fresh pork	Ext shel days the w ba anti a
17	Gelatin	-	Chilli oil	chicken	Redu loss, a oz
18	Gelatin	-	Beetroot peel extract	Beef	Incre life b cl oxic in sens
19	Soy protein isolates	-	Omega-rich oil	Beef burger patties	Imp char along life, m grow
20	Casein	Chitosan	Catechin	Chicken meat	In antio anti

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	ACTIVE COMPONENT	MEAT PRODUCT	OBSERVATION
					pro
21	Casein	-	<i>Zataria multiflora</i> EO	Smoked Caspian roach	E agai pos gran ba exte sh

PLA, polylactic acid; PCL, polycaprolactone; PHB, polyhydroxybutyrate; EO, essential oil

8.5.4 Cellulose

Cellulose is produced through photosynthesis, a macromolecular polymer made of β -d-glucopyranosyl groups attached by β -1,4 glycosidic bonds ([Zhou et al., 2022](#)). They are obtained from agricultural residues, wood, food waste, cotton, and bran of cereals ([Liu et al., 2021](#)). Recently, cellulose has been used in the packaging industry due to its wide availability, biodegradability, low weight, reinforcing capacity, and impressive mechanical properties ([Shaghaleh et al., 2018](#)). Particularly, the TS of the crystalline cellulose is 7.5–7.7 GPa, and Young's modulus is 110–220 GPa ([Liu et al., 2019](#)). As cellulose is biodegradable and has good physical and mechanical properties, it was used to pack many food components, specifically meat, where many have successfully extended meat shelf life. Carboxymethyl cellulose film consisting of nano-formulated pomegranate extract has extended beef and chicken meat's shelf life for 12 days by improving antioxidant and antimicrobial activity of the meat ([Khalid et al., 2024](#)), starch and polyvinyl alcohol-based films incorporated with clove oil applied on ground chicken meat showed inhibition toward gram-positive

food pathogens and extended the shelf life of the meat ([Muppalla et al., 2014](#)) ([Table 8.2](#)).

8.5.5 Alginate

The naturally occurring polysaccharides can be derived from different sources, which have received significant attention in the packaging industry. Alginate is derived from brown seaweeds like *Ascophyllum nodosum*, *Laminaria hyperborea*, and *Macrocystis pyrifera* ([Mostolizadeh, 2024](#)). Alginates have various applications, such as thickening agents, encapsulation, gel formation, membranes, and films. The alginate coating or wrapping on meat helps the meat retain its color, prevents shrinking, and keeps the sensory properties of the meat intact by providing good flavor and texture. The coatings also help to decrease the cooking loss and oxidative rancidity and increase the tenderness of meat ([Senturk Parreidt et al., 2018](#)). The promising characteristics of alginate help develop an intelligent and active packaging material. The films can be integrated with efficient components like indicators, antimicrobials, and antioxidants to maintain quality and enhance shelf life. Studies show that incorporating fish protein hydrolysates generated by protease ([Rathod et al., 2024](#)) from *Bacillus siamensis* F2 ([Rathod et al., 2023](#)) as an active component into sodium alginate and coating it on chicken fillets extends their shelf life up to 21 days ([Sadiya et al., 2025](#)). Sodium alginate and gelatin films incorporated with date pit extract improved films' physical, optical, and biodegradable properties ([Elhadeb et al., 2024](#)), and the development of multifunctional alginate films incorporated with carboxylated cellulose nanocrystals and extracts of beetroot was made to detect the spoilage of pork ([Guo et al., 2023](#)). The edible alginate films contain pineapple peel, a natural antioxidant that preserves beef meat ([Lourenço et al., 2020](#)) ([Table 8.2](#)).

8.5.6 Chitosan

Chitosan is one of the most unique polysaccharides due to its wide application in various pharmaceutical, biomedical, textile, cosmetic, and

food industries. Due to its wide use in the food industry, it has been used as a natural alternative to synthetic additives. Its promising properties, like antioxidant, nontoxicity, antimicrobial, biodegradability, and film-forming abilities, make it a good natural food packaging and preserving agent ([Fernando et al., 2024](#)). The meat's quality is majorly affected by the oxidation process of the meat, as chitosan is a good antioxidant agent that can prevent the oxidation process and extend the meat's shelf life ([Liu et al., 2022](#)). Various studies have been performed on chitosan, where the meat's shelf life, such as chitosan films incorporated with *Thymus vulgaris* L. EO (commonly known as thymol), showed good antimicrobial properties and water condensation in ready-to-eat meat ([Quesada et al., 2016](#)). In another study, chitosan coating and vacuum packaging were used on beef to extend its shelf life by preventing microbial growth and preserving it from spoilage ([Duran & Kahve, 2020](#)). Chitosan and alginate cling films were made by reinforcement of nanocomposites to extend the shelf life of red meat ([Pandey et al., 2024](#)), as depicted in [Table 8.2](#).

8.5.7 Gelatin

A yellowish or white lustrous solid with a translucent compound found in an animal's connective tissues. It can be widely used in gel formation, foam formation, emulsifying agents, film forming, and pharmaceuticals ([Lu et al., 2022](#)). In the food industry, meat is one of the most perishable foods, deteriorating quickly. The shelf life of meat products can be extended by adding edible coatings as a layer or using biopolymer films. Gelatin can be used widely to prevent meat spoilage by including some active components such as bovine gelatin solution spray-coated on beef tenderloins, pork loins, salmon fillets, and chicken breast, where this coating is acting as a barrier against water loss ([Antoniewski et al., 2007](#)), gelatin films impregnated with chili seed oil to enhance the poultry meat's shelf life ([Rather et al., 2024](#)), and beetroot extract was added to gelatin films where the beef meat was packed ([Chaari et al., 2022](#)), which reduced microbial growth ([Table 8.2](#)).

8.5.8 Casein

Casein is mainly a milk protein, which is important due to its nutritional properties. Caseins are widely used in the development of nanoparticles, hydrogels, emulsions, and film formation, making them a good base for the formation of the film ([Ranadheera et al., 2016](#); [Marudova et al., 2024](#)). The use of casein as a meat preservative material through its films and coatings enhanced the meat quality and shelf life, where casein-chitosan edible coating on chicken meat formed a good preservative coating on meat by preventing microbial growth and oxidation ([Apriliyani et al., 2020](#)). Casein films incorporated with *Zataria multiflora* EO (commonly known as Shirazi Thyme) to extend the shelf life of smoked Caspian roach ([Emam-Djomeh et al., 2016](#)) ([Table 8.2](#)).

8.5.9 Soy

Soy is one of the cheapest sources to produce soy protein isolates (SPI), which are widely available and used in food packaging. The films made from SPI can be an alternative to synthetic polymers ([Akrami et al., 2023](#)). Its applications include foaming, emulsifying, gelling, water-holding capacity, formation of hydrolysates, and film formation ([Ashaolu, 2020](#)). The SPI is widely used for the preservation of meat and meat products, which includes soy protein coatings on beef patties ([Guerrero et al., 2015](#)), soy edible coating on ground beef patties containing thyme and oregano EOs ([Kodal Coşkun et al., 2014](#)), and application of SPI-based films on burger patties of beef ([Hamed et al., 2024](#)). These coatings extended the shelf life by preserving meat's color, taste, and microbial contamination ([Table 8.2](#)).

8.5.10 Essential Oils (EOs)

Considering all the natural composites studied, EOs are natural antioxidant and antimicrobial compounds that enhance the quality of meat and meat products ([Araújo et al., 2018](#)). Various aromatic plants extract EOs as active

components, and biodegradable polymers extend the shelf life of food materials like meat, vegetables, and fruits. Meat storage using EOs prevents microbial contamination, lipid oxidation, and spoilage ([Smaoui et al., 2022](#)). The studies where the oils are used as the active components, including oregano or thyme oils, are used to extend the shelf life of lamb meat ([Karabagias et al., 2011](#)). Carvacrol, thymol, and cinnamaldehyde are used as antimicrobial agents to extend the shelf life of camel meat ([Osaili et al., 2021](#)). Black cumin EOs increased the shelf life of chicken breast fillets ([Takma & Korel, 2019](#)).

8.5.11 Wax

Waxes are lipid materials that are crystalline in form with long-chain fatty acids, hydrocarbons, ketones, fatty alcohols, and aldehydes. The waxes are food grade, easily available, cheap, and not sensitive to pH and salts. The application of waxes on several food products like fruits, vegetables, and meat is performed to obtain the shine on their surface; some of the edible waxes include beeswax, carnauba, and paraffin ([Soleimanian et al., 2020](#)). Various studies were done on meat using wax as a preserving agent, such as zein wax on veal meat chunks ([Fayed & El-Soud, 2022](#)), palm wax on ground beef ([Syahida et al., 2021](#)), and berry wax on rabbit meat ([Khan et al., 2024](#)), which are used to enhance the quality and extend the shelf life of meat.

8.5.12 Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates are intracellular compounds that are stored in some microorganisms, such as *Ralstonia eutropha*, *Paracoccus denitrificans*, *Rhizobium meliloti*, *Chromatium violacea*, *Thiocystis violacea*, and *Thiocapsa pfennigii*, as energy reserved under stress ([Suriyamongkol et al., 2007](#)). PHAs have low crystallinity and water vapor permeability, similar to LDPE. Polyhydroxybutyrate (PHB) is the most common form of PHA, and it is a biodegradable thermoplastic polymer with a crystalline nature ([Siripurapu et al., 2022](#)). It has a melting temperature of 180°C and 55°C

Tg ([Pawar & Purwar, 2013](#)). When PHA-based films are used as meat packaging, several advantages are noticed—PHA can be made into a flexible or rigid film. This is important for the seafood and meat industries as it is important for quality preservation, maintaining high standards, and extending the product's shelf life. Antimicrobial agents are often added to these films for improved preservation against microorganisms during transportation and storage. It enhances the barrier properties, including oxygen permeability and moisture resistance, preventing lipid oxidation and spoilage ([Kusuma et al., 2024](#)). Components such as nisin extend the shelf life from 7 to 28 days and are effective against *Lactobacillus plantarum* inoculated on ham ([Correa et al., 2017](#)). Fennel oil reduced the microbial count, displayed low TVBN, and prevented a drastic reduction in the pH in oysters ([Miao et al., 2019](#)).

8.6 PHYSICAL PROPERTIES OF VARIOUS MEAT PACKAGING FILMS

When PLA-PHB-fennel (FEN) oil films were prepared and applied on oysters, which prolonged the shelf life of oysters for two to three days, and the water vapor permeability (WVP) of $4.30 \text{ g m}/[\text{m}^2 \text{ s Pa}]\times 10^{-8}$, oxygen transmission rate of $513.9 \text{ cm}^3/\text{m}^2 \text{ d } 0.1 \text{ MPa}$, and antimicrobial property against *E. coli* and *Staphylococcus aureus* are key attributes responsible for the extension of shelf life ([Miao et al., 2019](#)). In a study, PLA was blended with nanocellulose, and the low WVP of $0.034 \text{ g mm}/\text{m}^2 \text{ h kPa}$ was the main reason for the shelf life extension of ground beef ([Talebi et al., 2018](#)). When the PCL composite was blended with PHB, the WVP value of $2.62 \pm 0.15 \times 10^{-11} \text{ g s}^{-1} \text{ m}^{-1} \text{ Pa}^{-1}$ led to an enhancement of the shelf life of ham ([Correa et al., 2017](#)). When nanofibrous films were developed using polycaprolactone (PCL) and alizarin, the film's WVP of $22.17 \pm 6.84 \text{ (g m}/\text{m}^2 \text{ s Pa)}\times 10^{-11}$ and characteristic color change from yellow to purple

(suggesting an association with TVB-N and the pH values) corresponds to the freshness of shrimp ([Zou et al., 2024](#)). When potato starch films impregnated with BHT (Butylated hydroxytoluene) and green tea extracts (GTE) were prepared, a water vapor transmission rate of 9.58 ± 0.461 g/m²/day and the addition of GTE extracts and BHT resulted in decreases in metmyoglobin, which extended the shelf life of beef ([Nisa et al., 2015](#)). In another study, when *Dioscorea zingiberensis* starch film was formulated with butterfly pea (*Clitoria ternatea* Linn.) flower extract (BPE) to monitor chicken freshness, the film's homogenous dispersion showed by FTIR and SEM, followed by designated color change (red to blue-violet and finally to green–yellow with increasing pH from 2 to 13), indicating meat's deterioration ([Wang et al., 2023](#)). When tapioca starch, cellulose nanocrystal, and each of grape pomace extracts [(Cabernet Franc (red variety) and Viognier (white variety)) blends were formulated and covered on ready-to-eat chicken, showed low water vapor permeability and exhibited an inhibitory effect on *S. aureus*, and Viognier films exhibited showed antibacterial activity *Listeria monocytogenes* ([Xu et al., 2018](#)). Film composites of starch-chitosan, pomegranate peel extract, and *Thymus kotschyianus* essential oil were prepared, and these films showed low water solubility values. When these films were used to cover beef, the shelf life was prolonged for 21 days ([Mehdizadeh et al., 2020](#)).

8.7 MECHANICAL PROPERTIES OF VARIOUS MEAT PACKAGING

The mechanical properties of biodegradable films, like TS, EAB, and Young's modulus, are critical for their performance in meat packaging ([Pires et al., 2021](#)). These properties determine the ability of the film to withstand external forces, maintain structural integrity, and adapt to the shape of the packaged product. High TS ensures the film can hold the weight of the meat without tearing, while good elongation at break provides

flexibility to accommodate irregular shapes ([Kumari et al., 2024](#)). They help prevent contamination and preserve hygiene by maintaining a barrier against oxygen, moisture, and microbes. Additionally, these properties ensure that the film endures the stresses of handling, transportation, and storage without compromising its functionality ([Prabhu & Prashantha, 2018](#)). Biodegradable films can effectively protect meat, maintain quality and safety, and provide a sustainable alternative to conventional plastics by optimizing mechanical properties ([Gheorghita et al., 2020](#)). Numerous studies have explored the application of biodegradable polymers in meat packaging, with their mechanical properties, as demonstrated in [Table 8.3](#).

8.8 THERMAL PROPERTIES OF VARIOUS MEAT PACKAGING

The thermal properties of biodegradable films are crucial for meat packaging, as they directly influence the film's performance under various storage, transportation, and processing conditions ([Wongphan et al., 2024](#)). The thermal properties mainly consist of glass transition temperature (T_g) and melting temperature (T_m). A film with an appropriate T_g ensures flexibility during refrigeration or freezing, preventing brittleness and maintaining mechanical integrity, and the T_m determines the film's ability to withstand mild heat treatments without deforming or losing its barrier properties ([Jafarzadeh & Jafari, 2021](#)). Additionally, heat sealability is vital for forming airtight seals, which minimize oxygen and moisture ingress, thereby extending the shelf life of meat ([Ilhan et al., 2021](#)). Low thermal conductivity further helps maintain stable internal temperatures, preventing rapid thawing or freezing, which could affect meat quality ([Zhang et al., 2023](#)). Several studies have explored the application of biodegradable polymers in meat packaging, emphasizing the importance of their thermal properties in ensuring product integrity and extending shelf life in [Table 8.4](#).

TABLE 8.3 Mechanical Properties of the Biodegradable Polymers Used in

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	MEAT PRODUCT	MECHANICAL	
				TENSILE STRENGTH (MPa)	YOUNG MODUL (GPa)
1	PLA	-	Ground meat	16.20±0.17	1.54±0.
2	PLA	-	Chicken breast meat	93±9	1133±1 MPa
3	PLA	-	Minced lamb	51.17±1.04	5.217±0.
4	PLA	Nanochitosan	Minced lamb	51±1	0.26±0.
5	PCL	-	Ground beef meat	491±54	-
6	PCL	-	Shrimp	1.89±0.18	-
7	PCL	Montmorillonite nanoclays	Ground beef meat	640± 76	-
8	PHB	PLA	Oysters	41.20±2.04	-
9	Potato starch	-	Fresh beef	1.7±0.003	0.193±0. MPa
10	Potato starch	Butylated hydroxytoluene	Fresh beef	6.4±0.02	3.254±0.
11	<i>Dioscorea zingiberensis</i> starch	Butterfly pea (Clitoria	Chicken	16.1±1.951	-

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	MEAT PRODUCT	MECHANICAL	
				TENSILE STRENGTH (MPA)	YOUNG MODUL (GPA)
		ternatea Linn.) flower extract			
12	Cellulose nanocrystal	Tapioca starch, grape pomace extracts	Ready-to-eat chicken	5.9±1.41	-
13	Chitosan	Starch, pomegranate peel extract, and <i>Thymus kotschyanus</i> EO	Beef	7.8±1.62	-
14	Gelatin	-	Chicken meat	9.6±3.93	-
15	Gelatin	Pectin	Chicken meat	7.22±0.75	-

PLA, polylactic acid; **PCL**, polycaprolactone; **PHB**, polyhydroxybutyrate

TABLE 8.4 Thermal Properties of the Biodegradable Polymers Used in the Preservation of Meat 

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	MEAT PRODUCT	THERMAL PROPERTIES		REFERENCE
				TG (°C)	TM (°C)	
1	Chitosan	Nanocellulose	Ground meat	115.88	97.44	(Dehnad 201

S. NO.	BIODEGRADABLE POLYMER	COPOLYMER	MEAT PRODUCT	THERMAL PROPERTIES		REFERENCE
				TG (°C)	TM (°C)	
2	PLA	Poly (ethylene-co-vinyl alcohol)	Pork meat fillets	67	148.9	(Hernández et al., 2021)
3	Gelatin	–	Chicken meat powder	81.02	–	(Hoque et al., 2019)
4	Potato starch	–	Beef	78.97	–	(Muhammad Nisa et al., 2019)
5	Nanocellulose	–	Pork	–	313.6	(Qian et al., 2021)
6	Carboxymethyl cellulose	Cellulose nanofiber		39	195.5	(Zabihollah et al., 2020)
7	Gelatin	–	Bigeye snapper fish skin	3.2	88.07	(Rasul et al., 2021)
8	PCL	–	Ground beef meat	–	59.7	(İlaslan et al., 2021)
9	Chitosan	–	Raw meat	272.73	–	(Rahman et al., 2019)
10	PLA	–	Chicken breast	–	160.77	(Zhao et al., 2021)

PLA, polylactic acid; **PCL**, polycaprolactone.

8.9 STRUCTURAL PROPERTIES OF MEAT PACKAGING

The structural properties of biodegradable films are essential for meat packaging, as they determine the film's mechanical strength, flexibility, and barrier effectiveness ([Kandeepan, 2021](#)). The internal molecular arrangement, degree of crystallinity, and interactions between components influence the film's ability to withstand external forces such as stretching, tearing, or puncturing during handling and transportation ([Wu et al., 2021](#)).

Fourier Transform Infrared Spectroscopy (FTIR) is crucial in evaluating the chemical structure of biodegradable films and their impact on meat packaging performance. FTIR influences the film's mechanical strength, flexibility, and barrier properties by identifying functional groups and molecular interactions, such as hydrogen bonding or crosslinking ([Azeredo & Waldron, 2016](#)). Functional groups like carbonyl, carboxyl, hydroxyl, and nitro are hydrophilic; however, methyl, ethyl, and phenyl are hydrophobic ([Gorbounov et al., 2024](#)). This affects the film's hydrophilicity or hydrophobicity, which is critical for controlling water vapor and oxygen permeability to prevent moisture loss, oxidation, and microbial spoilage of meat ([Li et al., 2019](#); [Qu et al., 2022](#)). The technique also confirms the incorporation of pure active agents, which enhance antimicrobial properties and extend the shelf life of meat. When fresh minced lamb meat was stored in PLA and nanochitosan films incorporated with *Polylophium involucre* EO, the FTIR peaks of resultant films for PLA were observed at wavenumbers $1,185\text{ cm}^{-1}$ (symmetric C–O ester stretching), $1,751\text{ cm}^{-1}$ (C=O ester carbonyl stretching), $1,452$ and $1,367\text{ cm}^{-1}$ (C–H bending), and $2,992\text{ cm}^{-1}$ (C–H asymmetric stretching); nanochitosan at $3,300\text{--}3,500\text{ cm}^{-1}$ (symmetric and asymmetric stretching vibration of N–H group); and *Polylophium involucre* EO at wavenumbers $1,084$ and $1,184\text{ cm}^{-1}$ (C–O stretching bonds of steric groups) and 869 cm^{-1} (C–C bonds) ([Bafroee et al., 2020](#)). In another study, the freshness of beef was monitored by packing

them in cornstarch, sweet whey, and red cabbage extract films. FTIR peaks of sweet whey were observed at $1,630\text{ cm}^{-1}$ (amine group I), $1,540\text{ cm}^{-1}$ (amine group II), and $1,337\text{ cm}^{-1}$ (amide group III); $3,289.88\text{ cm}^{-1}$ (stretching of the OH bond) related to the hydrogen bonds established between the components sweet whey, glycerol, starch, and red cabbage; anthocyanin of red cabbage extract at $1,750$ to $1,500\text{ cm}^{-1}$ (C=C, C=O, and C=N groups) and $3,000\text{--}37,00\text{ cm}^{-1}$ (OH bond) ([Sanches et al., 2021](#)). The FTIR for the active food packaging films provides insights into the molecular interactions, functional groups, and chemical composition. The FTIR analysis helps develop biodegradable films that effectively preserve meat products' freshness, safety, and quality during storage and transportation.

X-ray diffraction (XRD) analysis of a biodegradable film provides critical insights into its crystalline and amorphous regions, significantly impacting its suitability for meat packaging. The degree of crystallinity determined by XRD directly influences the film's mechanical strength, flexibility, and barrier properties. Amorphous regions contribute to the film's flexibility, ensuring it can wrap tightly around irregularly shaped meat products without cracking. On the other hand, higher crystallinity typically enhances the film's resistance to gas and moisture permeability, which is essential for preventing oxygen ingress and water vapor loss that can lead to meat spoilage ([Guinault et al., 2010](#)). When chicken meat was packed in a PLA, silver-copper (Ag-Cu) nanoparticle, and cinnamon EO composite film, PLA exhibited a characteristic semi-crystalline structure with a broad diffraction peak at 17° , Ag-Cu nanoparticles at 37.4° , 44.8° , 64.8° , and 77.5° , confirming the successful integration of the nanoparticles. Additionally, the inclusion of cinnamon EO does not alter the film's basic amorphous structure after compression molding, ensuring compatibility and structural stability ([Ahmed et al., 2018](#)). In another study, meat samples were wrapped in tamarind seed starch, okra mucilage, CMC, savory EO, and ZnO/ferrous oxide (FeO) nanoparticles. The XRD diffraction spectra of ZnO nanoparticles revealed distinct crystallographic reflections

characteristic of their structural patterns. ZnO nanoparticles displayed a pure wurtzite structure, confirmed by reflections at (100), (101), (002), (110), (102), (200), (103), (201), and (112) planes. Meanwhile, in FeO nanoparticles, the spectra indicated an octahedral and tetrahedral arrangement typical of pure magnetite, with reflections observed at (111), (311), (220), (422), (400), (440), (533), and (511) planes ([Chandrasekar et al., 2024](#)). XRD determines the crystallinity, polymer-additive interactions, and nanoparticle dispersion. Thus, XRD is a valuable tool for optimizing the structural properties of biodegradable films for effective meat preservation.

8.10 MORPHOLOGICAL PROPERTIES OF VARIOUS MEAT PACKAGING

The morphological properties of biodegradable films are crucial for meat packaging as they determine surface smoothness, uniformity, and the presence of defects like pores, voids, or cracks. Smooth, defect-free films provide excellent barriers against oxygen, moisture, and microbial penetration, essential for preserving meat quality and extending shelf life ([Wang et al., 2018](#)). Conversely, irregular surfaces or voids can compromise barrier performance and mechanical integrity, leading to spoilage risks ([Liu et al., 2024](#)). Optimizing these properties ensures durable, protective, and effective packaging for meat products.

Scanning Electron Microscopy (SEM) provides critical insights into biodegradable films' surface morphology and cross-sectional structure, directly influencing their performance in meat packaging. The surface smoothness observed through SEM affects the film's barrier properties; smoother surfaces typically exhibit better resistance to oxygen and moisture, reducing the risk of meat spoilage ([Wang et al., 2018](#)). Conversely, surface irregularities, such as pores, cracks, voids, or defects, can allow the entry of gases, moisture, or microbial contaminants,

compromising the film's integrity ([Liu et al., 2024](#)). SEM also reveals the distribution and compatibility of components in composite films ([Luo et al., 2012](#)). In a study where meat samples were wrapped in tamarind seed starch, okra mucilage, savory EO, CMC, and ZnO/FeO nanoparticles composite films, the film's SEM results showed that the coating surface showed the presence of component masses (self-esterification) as the composition consisted of both soluble and insoluble components, and the addition of glycerol and savory EO prevented roughness in the film. The coating's dense, compact structure and uniformly distributed spherical particles (< 300 nm) enable controlled release of EO. Incorporating nanoparticles and EO forms hydrogen and molecular bonds with CMC's carboxyl and hydroxyl groups, improving cohesion and penetration ability ([Ghasemi et al., 2024](#)). Thus, SEM analysis is vital for optimizing biodegradable films to ensure they effectively preserve meat quality and extend shelf life.

8.11 ACTIVE AND INTELLIGENT PACKAGING TO EXTEND THE SHELF LIFE OF MEAT

8.11.1 Active Packaging

Active packaging provides a barrier to external conditions and controls the internal environmental conditions of the packed food materials like meat, vegetables, and fruits ([Fang et al., 2017](#)). Techniques used for active packaging contain substances that detect ethylene, oxygen, moisture, odors, and CO₂, where some components release antioxidants, flavors, and antimicrobial components that protect the food and extend the shelf life ([Yildirim et al., 2018](#)). There are two different ways of preventing meat spoilage using active packaging, like direct and indirect interaction of packaging material with food, where the active packaging will be in direct

contact with food as a layer on the food material to prevent spoilage, whereas indirect contact of active packaging will be releasing the antimicrobial agents into the packaging system ([Yildirim et al., 2018](#)).

Biodegradable active packaging has several applications in extending the shelf life of meat and meat products by reducing factors responsible for spoilage, such as lipid oxidation, microbial growth, and moisture loss. Some of the results mentioned next showed the application of biodegradable active packaging to extend the shelf life of meat and meat products. When pork tissues were packed using nisin and ethylenediaminetetraacetic acid (EDTA) along with thermoplastic starch and poly(butylene adipate terephthalate) (PBAT), nisin and EDTA reduced lipid oxidation and microbial growth in the pork tissues, stabilizing redness and preventing discoloration and spoilage ([Leelaphiwat et al., 2022](#)). In another study, the chicken thigh was coated with an edible coating of alginate nanoparticles, menthol, and *Zataria multiflora* essential oil. This coating demonstrated the lowest yeast, mold, *Pseudomonas* sp., and aerobic mesophilic bacteria counts. It also demonstrated the highest antioxidant activity, lowest thiobarbituric acid reactive substances, total volatile basic nitrogen, and pH, showing the highest sensory attributes (color, odor, texture, and overall acceptability) ([Ranjbar et al., 2024](#)). There are two types of active packaging—scavenging objects and releasing objects ([Beshai et al., 2020](#)).

8.11.1.1 Scavenging Objects

Scavenging objects in active packaging for meat helps maintain quality, extend shelf life, and ensure safety by actively interacting with the internal environment of the package. Oxygen scavengers absorb oxygen to prevent spoilage caused by aerobic bacteria and molds, commonly using materials like iron powder or ascorbic acid. Moisture scavengers regulate humidity levels by absorbing excess moisture, preventing microbial growth, and are often made from silica gel or desiccants ([Li et al., 2022](#)). These active packaging systems, integrated into meat products, optimize conditions to

prevent spoilage, improve storage, and maintain quality. By incorporating these scavengers, meat products can stay fresher for longer, with reduced microbial contamination and enhanced consumer trust.

Oxygen absorbers are critical in active packaging for meat and processed meat products. They reduce oxygen levels within the packaging environment, minimizing oxidative reactions and microbial growth ([Prasad & Kochhar, 2014](#)). They help prevent transient discoloration of meat products, maintaining fresh and processed meats' natural color and appearance. Additionally, their use under controlled temperatures, such as 2°C, supports cold chain integrity, further slowing spoilage. They are effective in meat packaging as they maintain low oxygen levels and significantly extend shelf life by maintaining the oxygen absorbers (< 10 ppm), preventing oxidative rancidity and spoilage ([Cichello, 2015](#)). In a study, ground beef was wrapped in a pouch made of chitosan consisting of an oxygen absorber sachet and an oxygen indicator, which enhanced the shelf life of beef for six days ([Chounou et al., 2013](#)).

An effective method to control excess moisture in packaging is using moisture scavengers, which regulate water activity to suppress microbial growth. Moisture absorbers/scavengers are commonly available in films, pads, and sachets, which regulate excess moisture in food during storage. Some polymers, like CMC and starch copolymers, are super-absorbent and have a strong affinity to moisture. They can be placed under meat products to absorb undesirable moisture and exudates released by the meat products ([Ahmed et al., 2017](#)). Some common companies producing moisture-absorbing packaging for meat are Kyodo Printing Co., Ltd., Japan (MOISTCATCH™), Sorbed India, India (SORBED India™), SEALPAC, Germany (Tenderpac®), Sealedair, USA (Dri-Loc®), SOCO Chemical, China (SOCO®), Sealedair, USA (Cryovac® Absorbent Pads), C-Airlaid Company, Russia (C-Airlaid), and McAirlaid Inc., USA (MeatGuard) ([Gaikwad et al., 2019](#)).

8.11.1.2 Releasing Objects

Releasing objects in active packaging for meat are compounds that actively release substances into the package to extend shelf life, ensure food safety, and maintain product quality. Antioxidant releasers prevent oxidative damage by releasing antioxidants, like ascorbic acid or vitamin E, which protect the meat from rancidity and nutrient degradation ([Beshai et al., 2020](#)). Antimicrobial releasers continuously release antimicrobial agents like EOs or silver ions into the packaging environment to inhibit the growth of harmful microbes, like bacteria and molds. These releasing objects work by maintaining optimal conditions inside the package, improving meat preservation while reducing the spoilage and contamination risk ([Duda-Chodak et al., 2023](#)). In a study, cornstarch-based films were prepared along with citric acid for conserving beef. It was observed that the migration of citric acid increased with the increase in storage period (10 days), reducing the oxidation and growth of microorganisms and providing a desirable color during storage ([Júnior et al., 2015](#)). In another study, it was observed that alginate, zein, and polyvinyl alcohol films were formulated to control *Listeria monocytogenes* during the storage of sliced cooked ham, where the shelf life of ham increased to 29 days ([Marcos et al., 2007](#)).

Flavor releasers release compounds that can enhance the aroma or flavor of meat, improving consumer appeal, especially in pre-cooked or ready-to-eat products. Some flavor components that are added to biodegradable polymers include thymol, oregano, basil, cinnamon, clove, rosemary, lemon, caraway, and vanillin ([Sanahuja & Valdés García, 2021](#)). They consist of volatile components that, when incorporated in the biodegradable polymer, act as active packaging, imparting flavors to the packaging. A study was conducted where PLA and PHA composites were made with oregano essential oil to study the flavor and quality of pufferfish fillets. It was observed that the oregano EO released active component carvacrol from the film to the pufferfish, thereby extending the quality and shelf life of the fillets ([Zheng et al., 2022](#)). By gradually releasing beneficial substances, these systems ensure that meat products stay fresh, safe, and flavorful throughout their shelf life.

8.11.2 Intelligent Packaging

Intelligent packaging involves using the packaging to access the food's surrounding environment and control or monitor the packed food ([Ghaani et al., 2016](#)). Many techniques are used to develop intelligent packaging: freshness, time and temperature, seal and leak indicators, sensors that monitor environmental conditions, quality indicators, and data carriers ([Müller & Schmid, 2019](#); [Pereira de Abreu et al., 2012](#)). Various studies have been performed on the techniques of intelligent packaging applied to fruits, dairy products, vegetables, and meat products. To develop intelligent meat packaging material, it is essential to understand the spoilage process of the meat as it is easily perishable food material. The important factors that cause meat spoilage are the pH and the composition of the meat product, water activity, temperature, humidity, and gaseous atmosphere. These important factors must be considered while developing intelligent packaging material ([Nami et al., 2024](#)). Various types of intelligent packaging include sensors, indicators, and data carriers, as demonstrated in [Figure 8.3](#).

8.11.2.1 Sensors

Sensors play a crucial role in developing intelligent packaging systems for meat and meat products, providing real-time detection and monitoring of spoilage and quality. Gas sensors, in particular, are widely used to measure the concentration of gases like oxygen, CO₂, ammonia, and volatile organic compounds (VOCs) within the packaging ([Mohebi & Marquez, 2015](#)). These gases serve as key indicators of spoilage in highly perishable items like meat. For instance, oxygen sensors can detect leaks in modified atmosphere packaging (MAP) ([Czerwiński et al., 2021](#)), where oxygen levels must remain low to prevent oxidation and microbial growth. Similarly, a rise in carbon dioxide levels within the package often indicates increased microbial activity, signaling potential spoilage ([Li et al., 2023](#)). Ammonia sensors detect the byproducts of protein breakdown, providing an early warning of meat degradation ([Naghdi et al., 2021](#)). By incorporating

these sensors, intelligent packaging enhances packaged meat products' safety, quality, and shelf life, ensuring consumer trust and reducing food waste. In meat packaging, chemical sensors are crucial in monitoring freshness and ensuring safety by detecting specific chemical compounds or spoilage-related changes ([Chiu et al., 2024](#)). These sensors often target VOCs like ammonia, hydrogen sulfide, or biogenic amines, released as meat degrades. Many chemical sensors utilize colorimetric indicators, where a visible color change signals chemical reactions linked to spoilage processes, such as shifts in pH or gas composition within the package ([Wanniarachchi et al., 2024](#)). By providing real-time data on meat quality, these sensors enable more accurate assessments of freshness, reducing reliance on static expiration dates. This enhances consumer safety by identifying spoilage risks early and minimizes food waste, as products are discarded based on actual conditions rather than conservative estimates. Chemical sensors integrated into meat packaging ensure better transparency, extended shelf life, and optimal handling throughout the supply chain ([Jafarzadeh et al., 2024](#)).

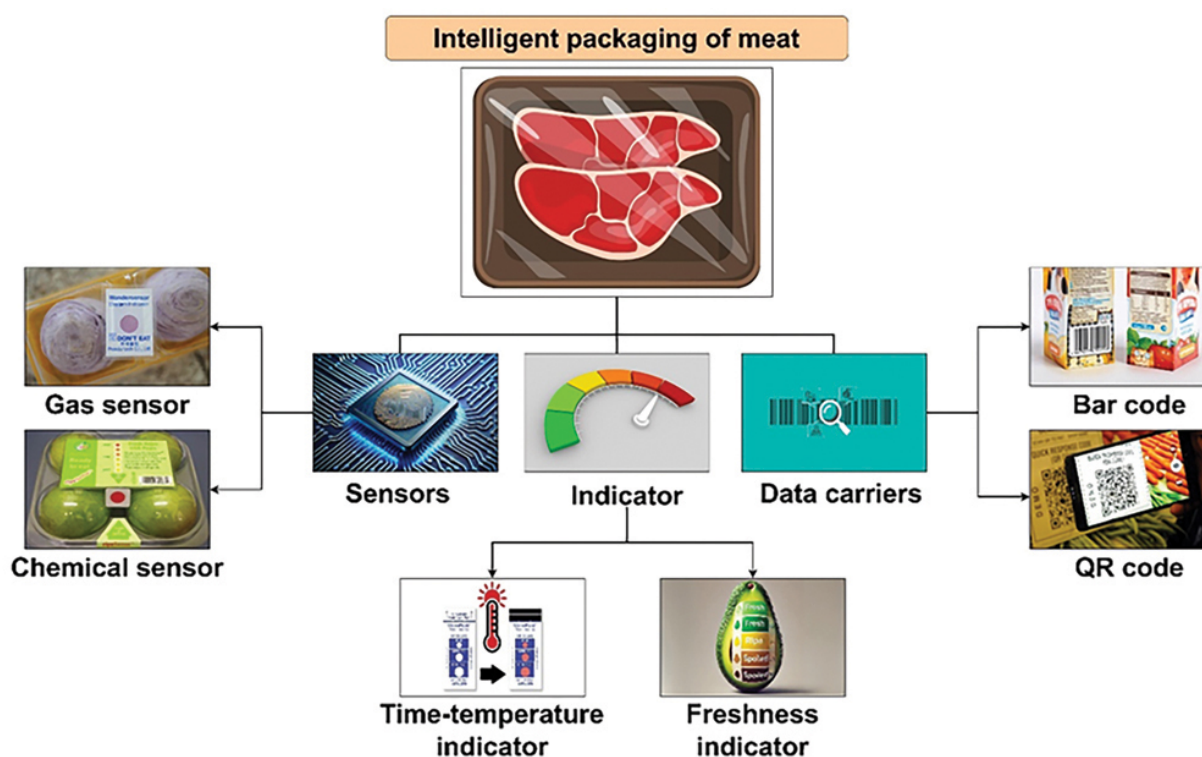


FIGURE 8.3 Intelligent packaging and their types. [📄](#)

8.11.2.2 Indicators

Indicators in intelligent packaging play an important role in monitoring and conveying information about the condition of packaged meat, ensuring its safety and quality throughout storage and distribution. Time-temperature indicators are extensively used in meat packaging to track the cumulative exposure of the product to temperature fluctuations ([Ma et al., 2022](#)). Meat is highly perishable, and time-temperature indicators ensure it remains within safe storage conditions by using color changes or visual cues to signal if it has been exposed to unsafe temperatures. This is vital for maintaining the safety of raw or processed meat products during transport and storage ([Mohebi & Marquez, 2015](#); [Nagaveni & Poosarla, 2024](#)). A study utilized *Janthinobacterium* sp. and its metabolite violacein to develop a microbial time-temperature indicator for monitoring the shelf life of pork. The violacein, a natural pigment produced by the bacterium, exhibited a distinct violet color associated with microbial activity over time. This colorimetric response accurately reflected the spoilage period, providing a reliable visual measure of pork's shelf life, which offers a promising tool for real-time monitoring of meat freshness, enhancing food safety, and reducing waste ([Mataragas et al., 2019](#)).

Similarly, freshness indicators are instrumental in monitoring the spoilage of meat. They detect chemical or microbial changes associated with meat degradation, such as shifts in pH, gas buildup (e.g., ammonia or hydrogen sulfide), or the release of metabolites like biogenic amines ([Y. Liu et al., 2024](#)). These indicators provide a visible signal, such as a color change, to reflect the freshness status, alerting consumers or distributors to potential spoilage. By offering real-time information about meat quality, these indicators enhance food safety, reduce waste, and bolster consumer confidence in meat packaging systems ([Ma et al., 2022](#)). In a study, the storage quality of beef was monitored using a freshness indicator developed using methyl red and cellulose acetate. A distinct color change (red to

yellow) was observed with the increase in storage period (0 to 72 h) at 20°C. A strong association was found between the chemical quality of beef and the color change of the freshness indicator, demonstrating beef's shelf life during storage ([Lee & Shin, 2019](#)). Another study detects the release of ammonia gas from pork stored at 50% relative humidity and three different temperature conditions—22 °C , 4 °C , and at a fluctuating temperature scenario of 22 and 4°C using radio frequency identification (RFID) tags as the decomposition of meat leads to the generation of ammonia and hydrogen sulfide gases ([Eom et al., 2014](#)).

8.11.2.3 Data Carriers

Data carriers, like Quick Response (QR) codes and barcodes, play a crucial role in intelligent packaging for meat products, bridging the gap between physical packaging and digital information. Barcodes, being linear and one-dimensional, store essential information such as product ID, price, and manufacturer details. They are commonly used in meat packaging for inventory management, retail checkout, and basic traceability ([Chowdhury & Morey, 2019](#)). On the other hand, QR codes offer a two-dimensional format that can store a larger volume of data, including batch numbers, slaughter and packaging dates, storage conditions, and expiration details. These codes, easily scannable with smartphones, allow consumers to verify the freshness and origin of the meat, view nutritional information, and access cooking instructions. In the supply chain, QR codes enable real-time tracking, ensuring transparency by recording transportation and storage conditions like temperature and handling practices. This interactive approach enhances food safety and traceability and builds consumer trust in the quality and authenticity of meat products ([Hung et al., 2020](#)).

Various studies have developed intelligent packaging that includes pigments such as curcumin, carotenoids, betacyanins, chlorophyll, and anthocyanins found in different plant parts like root, stem, leaf, bark, and flower. These pigments show good functional properties like pH sensitivity, antioxidant, and antibacterial activity ([Lv et al., 2023](#)). A study where an

intelligent packaging material containing tragacanth gum-pectin (TG-PE), *Althaea officinalis* extract (AOE, 3 g/100 mL), and chitin nanowhiskers (CNW, 1 and 2 g/100 mL) was made to perform shelf-life studies on chicken fillets to determine the pH of the fillets during the storage period. [Figure 8.4](#) shows the changes in the freshness of chicken fillets under cooled conditions, using TG-PE and AOE-3; TG-PE, AOE-3, and CNW-1; and TG-PE, AOE-3, and CNW-2 nanofiber mats after 0, 2, and 4 days, where TG-PE + AOE-3 + CNW-1 and TG-PE + AOE-3 + CNW-2 nanofiber mats can be used to monitor the change in chicken fillets' quality as intelligent packaging indicators ([Khazaei et al., 2024](#)). In another study, films were fabricated using starch extracted from the waste seeds of *Artocarpus lakoocha* and curcumin to develop intelligent packaging and estimate the shelf life of chicken fillets. It was observed that with the increase in storage period (day 0 to 10), the pH of the chicken increases, leading to a change in color of the film from transparent yellow to a darker orange-red color ([Mali & Pandey, 2024](#)). A similar color change was observed in a study where anthocyanin extracted from dried barberry fruits was added to chitosan nanofibers and methyl cellulose films to monitor the freshness of lamb meat stored for 72 hours at 25 °C. Amines and ammonia are released due to the degradation of proteins, thereby increasing the pH of the meat. This pH change was indicated by the film, which changes from a reddish color to pale peach ([Alizadeh-Sani et al., 2021](#)).

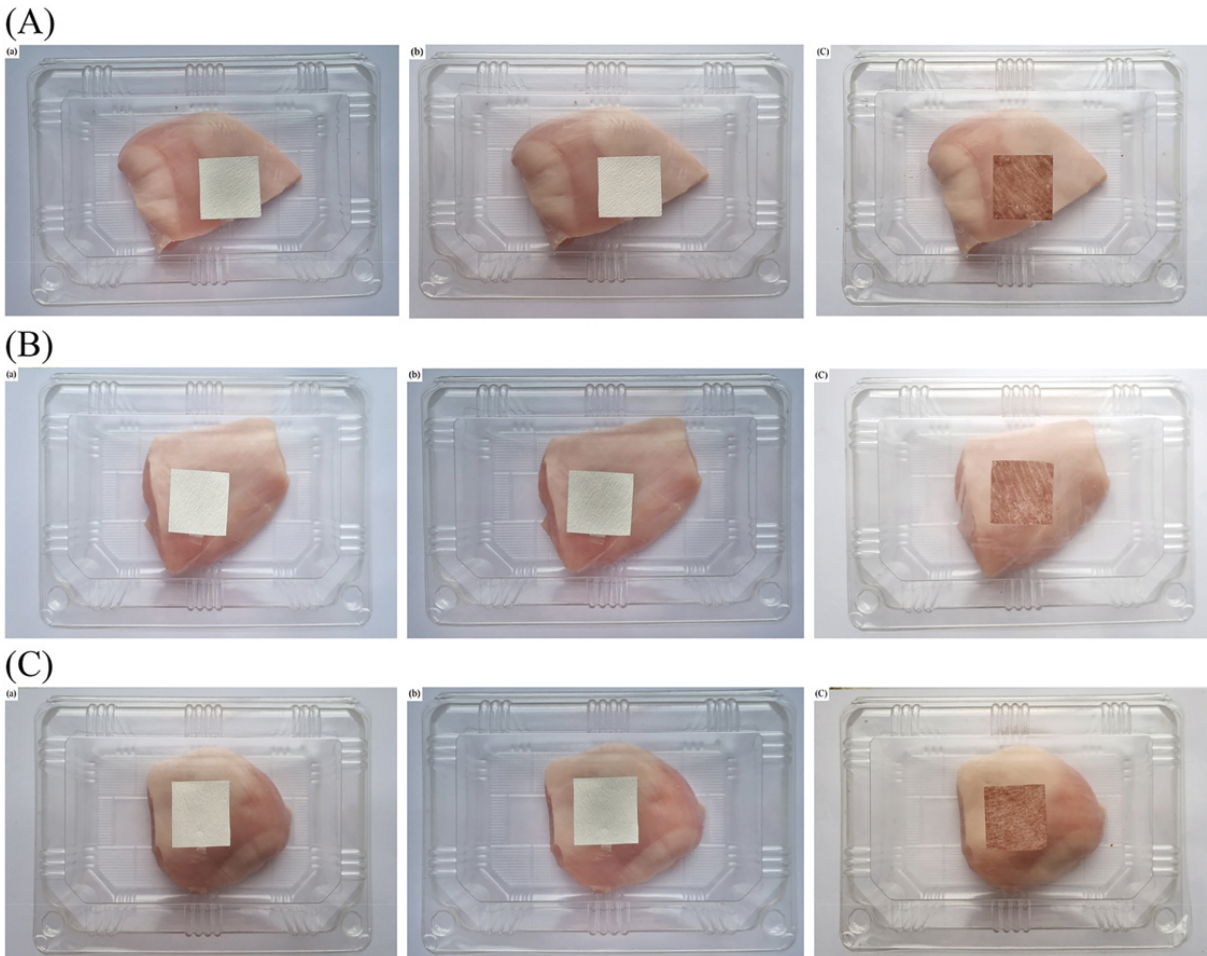


FIGURE 8.4 Changes in the freshness of chicken fillets under cooled conditions using TG-PE + AOE-3 (A), TG-PE + AOE-3 + CNW-1 (B), and TG-PE + AOE-3 + CNW-2 (C) nanofiber mats after 0 (a), 2 (b), and 4 (c) days. TG: tragacanth gum, PE: pectin, AOE: *Althaea officinalis* extract, CNW: chitin nanowhiskers ([Khazaei et al., 2024](#)). 

8.12 ENVIRONMENTAL BENEFITS OF SUSTAINABLE PACKAGING MATERIALS

In recent years, meat consumption has gradually increased, and the growing demand for proper meat packaging has also been rising. The safety, maintenance of quality, good taste, health benefits, and legal requirements must be considered. The development of packaging material by the

producers has to be done according to the requirements of consumers by adapting to the needs by increasing the product's shelf life ([Soro et al., 2021](#)). The packaging for meat and meat products is vital for maintaining durability and sustainability, as plastics are considered harmful to the environment due to their nonbiodegradability. To address the problem of plastic materials, sustainable packaging materials that can be biodegradable, recyclable, and reusable should be developed, and this will also save the economy. Also, it increases the shelf life of the food by acting as a primary layer that acts as a preservative toward the food material ([Wikström et al., 2019](#)). The storage of poultry, meat, and seafood is well maintained by freezing. The packaging used should be chosen wisely, as a product with low-quality packaging material can lead to weight loss due to sublimation. The sustainable packaging material for poultry and meat products can be non-edible or edible films made of starch, pectin, alginate, and cellulose. These compounds are sustainable packaging materials that help extend the shelf life of meat by maintaining quality by preventing browning, oxidative rancidity, and dehydration ([Ibrahim et al., 2022](#)). With the utilization of these biodegradable materials, the packaging material developed is beneficial to the ecosystem, and according to Corporate Social Responsibility, sustainable packaging is considered a new addition to the environment, as they are made up of eco-friendly materials and promotes a sustainable environment. Using sustainable packaging benefits manufacturers and consumers as it reduces the environmental effects and promotes a clean and sustainable environment for the coming generations ([Rajesh & Subhashini, 2021](#)).

8.13 CHALLENGES

Despite the significant environmental benefits of biopolymer-based packaging, several challenges hinder its widespread adoption of meat packaging. Mechanical strength is one of the primary issues of

biodegradable polymers derived from starch. They have low mechanical durability and can be prone to brittleness, making them vulnerable during handling and transportation ([Cazón et al., 2017](#)). As reported in a study, frankfurter sausages were coated using turmeric starch and gelatin films, where the TS of turmeric starch (4 MPa) films was lower than gelatin films (13 MPa) and the blend of turmeric starch and gelatin films (5MPa). Additionally, biopolymers absorb water due to their hydrophilic nature, leading to swelling and compromised moisture and water vapor barrier properties ([Garavand et al., 2017](#)). The hydrophilic nature of thermoplastic starch ([Castro-Rosas et al., 2016](#)) and chitosan ([Rahman et al., 2017](#)) leads to poor barrier properties, limiting their effectiveness in meat packaging ([Wang et al., 2020](#)).

The oxygen barrier performance of biopolymer films is another major concern, as it can lead to oxidative spoilage, discoloration, and microbial growth in meat. The combined effect of microbial deterioration and chemical changes reduces meat products' shelf life ([Sun & Holley, 2012](#)). Traditional synthetic polymers offer superior oxygen impermeability, while many biodegradable films, such as those made from chitosan, require coatings to achieve a superior oxygen barrier property ([Umaraw et al., 2020](#)). Similarly, a multilayer structure of PLA was prepared to retain the quality and enhance the shelf life of pork fillets, thereby enhancing the oxygen barrier properties ([Hernández-García et al., 2022](#)). Moreover, thermal stability poses a challenge, especially in applications requiring heat sealing or sterilization. Many biopolymers degrade or lose functionality at elevated temperatures, limiting their use in high-temperature processes. PLA is one such biopolymer with low thermal stability; however, this challenge can be overcome by blending other polymers ([Wang et al., 2022](#)) or nanoparticles ([Negahdari et al., 2021](#)). Furthermore, scalability and production costs remain significant obstacles. The high cost of raw materials and processing of biopolymers results in higher production costs than conventional plastics ([Naser et al., 2021](#)). Addressing these challenges requires further research into advanced biopolymer composites, cost-

effective production techniques, and the development of recycling and composting infrastructures.

8.14 FUTURE PROSPECTS

The future of sustainable packaging materials in fresh meat and meat products is promising because it provides an excellent solution to reduce the impact of the environment on plastic-based meat packaging. Sustainable packaging materials derived from plants, animals, seaweed, and fungal-based materials are studied as alternatives to plastics. These are biodegradable, reducing the plastics and edible, which can be consumed along with the food material ([Cenci-Goga et al., 2020a](#)). The development of packaging materials from circular economy models made of waste produced from agricultural by-products contributes toward reducing environmental footprints by recycling and reusing the materials ([Panda et al., 2024](#)). The advancements in the development of 3D printing material minimize waste by fitting the shape and the size of the meat cuts and can also customize packaging ([Rogers & Srivastava, 2021](#)). As the consumers' demand for sustainable packaging increases, the meat industry adopts eco-friendly packaging material to meet the food industry's struggle to develop environmentally friendly packaging material ([Chhetri et al., 2024](#)). Future packaging materials will be shaped by combining biodegradable materials with innovative technologies and sustainable practices, ultimately decreasing plastic waste and improving the impact on the industrial environment.

8.15 CONCLUSION

In conclusion, developing sustainable materials for packaging fresh meat and meat products offers a promising solution to mitigate the environmental challenges posed by traditional plastic packaging. Biodegradable materials like PHA, PLA, and starch-based films reduce the ecological footprint and enhance the shelf life and quality of meat by serving as effective barriers against contamination and physical damage. Furthermore, advancements in intelligent and active packaging technologies significantly enhance the functionality of these materials by incorporating features like antimicrobial properties, freshness indicators, and improved gas permeability. These innovations provide eco-friendly and efficient alternatives to conventional plastics, aligning with the growing consumer demand for sustainable packaging. As the meat industry transitions toward greener practices, these solutions will play a critical role in shaping an environmentally responsible future while maintaining product safety and quality.

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Sustainable Biomaterials for Dairy Products 9

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9.1 INTRODUCTION

The global dairy industry is among the largest food sectors, playing a pivotal role in nutrition and economic development by producing milk, cheese, yogurt, butter, and other derivatives ([Rejeesh & Anto, 2023](#)). These products, however, are perishable and thus require specialized packaging that maintains quality, prevents spoilage, and ensures safety along the supply chain ([Dipierro et al., 2018](#)). Traditional packaging solutions have historically focused on functionality and cost-effectiveness, but growing concerns about climate change, resource depletion, and pollution have heightened the call for more sustainable alternatives ([Singh et al., 2024](#); [Sinha, 2024](#)).

As global demand for dairy continues to rise, so does awareness of the environmental footprints associated with packaging practices. Dairy products account for a significant proportion of single-use plastics within the food sector, contributing substantially to waste accumulation worldwide ([Li et al., 2017](#)). Consequently, the sector faces the challenge of balancing efficient food preservation with reduced ecological impact ([Ortega et al., 2017](#)).

Recent years have seen a wave of public concern and legislative actions aimed at minimizing plastic pollution, exemplified by the European Union's Single-Use Plastics Directive and sustainable packaging policies promoted by regulatory bodies such as the U.S. FDA ([Jafarzadeh et al., 2021a](#)). Stakeholders—from government agencies and environmental organizations to consumers—have amplified the pressure for dairy producers to adopt packaging that is not only high-performing but also eco-friendly ([Rejeesh & Anto, 2023](#)).

Conventional dairy packaging typically relies on petroleum-derived plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). These materials offer excellent barrier properties and durability at low cost, fulfilling most technical requirements for product integrity ([Ryder et al., 2017](#)). However, their resistance to degradation results in persistent plastic waste in landfills and marine ecosystems, generating widespread contamination by microplastics and posing a threat to wildlife and human health ([Ortega et al., 2017](#); [Jafarzadeh et al., 2021a](#)).

Additionally, the carbon footprint of producing and disposing of these polymers is substantial: extracting fossil fuels, refining them, and subsequently polymerizing them demand large amounts of energy, thereby contributing to greenhouse gas emissions ([Singh et al., 2024](#)). Limited recycling infrastructure further compounds the issue; a large share of dairy packaging is either incompatible with existing recycling streams or poorly recycled in practice, leading to high rates of incineration or landfill use ([Li et al., 2017](#)). In response, governments worldwide have imposed stricter regulations to curtail plastic waste and encourage more sustainable solutions.

9.2 THE NEED FOR SUSTAINABLE PACKAGING IN THE DAIRY SECTOR

The transition to sustainable dairy packaging arises from a combination of regulatory mandates, consumer demand, and corporate responsibility. Public and private initiatives converge on reducing the environmental burden while retaining food safety, barrier efficacy, and cost-effectiveness ([Sinha, 2024](#)). Various eco-friendly biomaterials have thus emerged, including the following:

- Polysaccharides (e.g., starch, cellulose, chitosan): Abundant, renewable sources with potential for biodegradable films.
- Proteins (e.g., casein, whey protein): Able to form edible or compostable films with good oxygen-barrier properties.
- Biodegradable synthetic polymers (e.g., PLA, PHA, PBS): Offer mechanical strength and thermal stability while being derived from renewable resources or enabling faster degradation.

Recent technological advancements—such as nanotechnology, active packaging, and multilayer films—have enhanced the mechanical and barrier performance of these materials, addressing challenges that historically limited their large-scale application ([Ryder et al., 2017](#)). Nonetheless, economic feasibility and scalability remain key barriers. Industry collaboration, policy support, and ongoing research are vital to overcoming these hurdles ([Martins & Romani, 2022](#)).

According to [Ghasemlou et al. \(2024\)](#), the food packaging industry is undergoing a rapid transition due to the advancement of bioplastics. Although they offer environmental benefits, their adoption faces challenges such as low biodegradability in some cases and a lack of infrastructure for industrial composting. Additionally, there are difficulties in consumer acceptance, often due to misinformation about bioplastics' properties and their compatibility with conventional recycling. However, global bioplastics

production capacity is expected to increase from 2.18 million tons in 2023 to approximately 7.43 million tons by 2028, reflecting a growing trend of investment in this sector ([Ghasemlou et al., 2024](#)).

9.3 FUNCTIONS AND REQUIREMENTS OF DAIRY PRODUCT PACKAGING

Packaging for dairy products must fulfill a range of roles that ensure food safety, quality preservation, and consumer appeal ([Dipierro et al., 2018](#); [Hamed et al., 2022](#)). This section examines the principal functions and requirements of dairy packaging, focusing on three major dimensions—protection and preservation, mechanical and structural properties, and sustainability—along with specific sensory and shelf-life considerations.

9.3.1 Protection and Preservation

9.3.1.1 *Physical Barriers*

Physical protection involves safeguarding dairy items from external contaminants, humidity, and mechanical impacts ([Jafarzadeh et al., 2021a](#)). For instance, bottles or films made from high-barrier materials minimize moisture migration and reduce the risk of product deformation during transportation ([Plóska et al., 2024](#)). Furthermore, corrugated cartons or rigid plastics can protect milk containers from compression, while flexible films shield cheese slices from abrasion and tearing ([Ortega et al., 2017](#)).

9.3.1.2 *Chemical Barriers*

Chemical barrier properties aim to avoid the migration of compounds—whether from packaging into the product or vice versa—and to maintain the sensory attributes of dairy ([Göksen et al., 2020](#)). Migratory substances can include plasticizers or residual monomers from conventional plastics, which

may impart off-flavors or compromise food safety ([Hamed et al., 2022](#)). Biopolymers such as chitosan or whey protein can be formulated into coatings that reduce oxygen permeation and minimize undesirable oxidations, thus retaining freshness and nutritional quality ([Dipierro et al., 2018](#); [Rejeesh & Anto, 2023](#)).

9.3.1.3 Biological Barriers

A key function of dairy packaging is controlling microbial activity. Cheese, yogurt, and milk are susceptible to spoilage microorganisms due to their high moisture and nutrient content ([Plóska et al., 2024](#)). Packaging materials that inhibit bacterial or fungal growth can effectively extend shelf life. For example, incorporating natural antimicrobials—such as plant extracts or organic acids—into polymer matrices (including polylactic acid or protein-based films) helps mitigate microbial proliferation ([Göksen et al., 2020](#); [Li et al., 2017](#)). In active edible coatings, substances with antimicrobial activity diffuse onto the product surface, reducing contamination and spoilage ([Jafarzadeh et al., 2021b](#)).

Recent research suggests that nano-bio packaging incorporating natural antimicrobials such as essential oils, polysaccharides, polypeptides, and enzymes has demonstrated a broad-spectrum antimicrobial action while maintaining cheese quality parameters such as pH, texture, color, and flavor ([Lima et al., 2021](#)). Future research should focus on the potential toxicological effects of these natural antimicrobials and their efficacy in active food packaging systems.

9.3.2 Mechanical and Structural Properties

9.3.2.1 Mechanical Strength

Mechanical strength implies the capacity to withstand handling, storage, and distribution without rupturing or deforming ([Ortega et al., 2017](#)). Rigid containers (e.g., for yogurt) need to endure stacking in warehouses, while flexible pouches (e.g., for processed cheese) must resist punctures. High

tensile strength ensures the integrity of packaging, preventing leaks or exposure to external contaminants ([Hamed et al., 2022](#)). Blending biopolymers with reinforcing agents, such as nanocellulose or starch nanocrystals, can enhance material strength while maintaining biodegradability ([Sinha, 2024](#)).

Flexibility is vital for forming diverse shapes—such as cheese wraps, portion-sized sachets, or pouches for dairy drinks—and for sealing methods ([Singh et al., 2024](#)). Thermoplastic polymers like polybutylene succinate (PBS) or polyhydroxyalkanoates (PHA) offer a balance of flexibility and ease of heat-sealing, allowing consistent closure and reduction of headspace ([Li et al., 2017](#)). Protein-based films (e.g., those derived from casein) can also exhibit plasticity when combined with suitable plasticizers, although they may require careful humidity control ([Dipierro et al., 2018](#)).

Consumer perceptions of freshness, color, and product quality are partly shaped by packaging aesthetics ([Plóska et al., 2024](#)). Transparent films let consumers visually assess cheese or other dairy items, a factor that can significantly influence purchasing decisions ([Rejeesh & Anto, 2023](#)). However, the interplay between transparency and light barrier capacity must be considered, as excessive light can accelerate the oxidation of fats and vitamins in milk or cheese ([Sinha, 2024](#)). Consequently, balancing clarity with adequate UV or visible light filtration remains crucial.

9.4 SUSTAINABILITY AND CIRCULAR ECONOMY

9.4.1 Biodegradability and Compostability

Biodegradability refers to the capacity of a material to decompose through microbial action, forming simpler substances such as water, carbon dioxide, and biomass ([Hamed et al., 2022](#)). Compostable packaging, on the other hand, must break down under specific composting conditions without

leaving toxic residues ([Sinha, 2024](#)). Biopolymers like polylactic acid (PLA) or starch-based blends commonly meet these criteria, especially under industrial composting standards ([Li et al., 2017](#)). In the dairy sector, ensuring that packaging decomposes after disposal can significantly reduce waste stream burdens.

9.4.1.1 Recyclability

Although biodegradable solutions are expanding, recyclability remains a key circular economy strategy—particularly for packaging streams with established recycling channels ([Plóska et al., 2024](#)). Some bioplastics, such as bio-based polyethylene (bio-PE) or polypropylene (bio-PP), maintain chemical structures compatible with conventional recycling yet originate from renewable sources ([Sinha, 2024](#)). The success of recycling programs in the dairy industry depends on consistent sorting, stable markets for recycled resins, and consumer participation ([Rejeesh & Anto, 2023](#)).

While recycling is a key strategy for the circular economy, its impact is limited by the low recycling rate of conventional plastics. It is estimated that only 10% of post-consumer plastic is currently recycled in Europe, while the rest is incinerated or sent to landfills ([Ghasemlou et al., 2024](#)). To address this issue, a promising approach is the gradual replacement of traditional plastics with recyclable bioplastics, such as bio-PET and bio-PE, which maintain compatibility with existing recycling streams. However, challenges such as the separation of bioplastics from conventional plastics and the economic feasibility of chemical recycling still need to be overcome.

9.4.1.2 Use of Renewable Resources

Sustainable dairy packaging capitalizes on renewable raw materials—like plant-based polysaccharides or dairy-derived proteins—that reduce reliance on fossil resources and minimize carbon emissions ([Ryder et al., 2017](#)). Byproducts such as whey, which is abundantly produced during cheese making, can be valorized into protein films, fostering synergy between

different parts of the dairy supply chain ([Dipierro et al., 2018](#)). Incorporating residues like cellulose fibers from agricultural waste or algae derivatives also exemplifies resource efficiency, advancing circular economy goals ([Hamed et al., 2022](#)).

9.5 SENSORY ASPECTS AND SHELF LIFE

9.5.1 Interplay between Packaging Barriers and Organoleptic Properties

Dairy products are often vulnerable to flavor and aroma shifts, particularly through contact with external contaminants or oxidation ([Göksen et al., 2020](#)). Packaging with suitable oxygen and moisture barriers preserves distinctive sensory profiles—especially crucial for specialty cheeses that contain nuanced flavor compounds susceptible to volatilization or oxidation ([Plóska et al., 2024](#)). Protein-based coatings can help retain desirable aromas while curbing rancidity by limiting oxygen exposure ([Li et al., 2017](#)).

Optimized packaging significantly extends the shelf life of milk, yogurt, and cheese. Materials that slow microbial growth or inhibit enzymatic reactions can keep dairy items fresher for longer, preventing both spoilage and economic losses ([Jafarzadeh et al., 2021b](#)). Antimicrobial packaging, for instance, embeds bacteriostatic or bactericidal agents—like essential oils or silver nanoparticles—into films to reduce contamination ([Göksen et al., 2020](#)). Active packaging approaches thus offer a dual benefit: sealing out external agents and actively inhibiting microbial proliferation within.

Sensory evaluation protocols (e.g., triangle tests and descriptive analyses) are essential for gauging consumer acceptance of new packaging solutions ([Singh et al., 2024](#)). Even if packaging effectively prolongs shelf life, it must not impart off-flavors, odors, or a distinct visual defect that discourages purchase ([Ortega et al., 2017](#)). Positive consumer feedback on

the taste and appearance of dairy products packaged in sustainable materials can catalyze broader market acceptance ([Hamed et al., 2022](#)).

TABLE 9.1 Summary of Key Packaging Requirements for Dairy Products, References [↗](#)

REQUIREMENT/BARRIER FUNCTION/RELEVANCE		SUITABLE MATERIALS/APPROACHES
Physical Barrier	Minimizes moisture migration, mechanical impacts, and external contamination.	- Rigid plastics (HDPE, PLA) - Laminated cardboard - Corrugated cardboard - Starch films reinforced with nanocellulose
Chemical Barrier	Preserves sensory attributes (flavor, odor) and prevents migration of plasticizers or residual monomers	- Chitosan-based film coatings - Casein or whey protein coatings - PLA with minimal residual monomers
Biological Barrier	Inhibits microbial growth, extending shelf life and ensuring food safety	- Antimicrobial packaging blends (chitosan + essential oils) - Casein-based edible coatings - Nano-Ag or nano-ZnO infused biomaterials
Mechanical Strength	Maintains packaging integrity in transit	- Biopolymer blends (starch, PLA-PI)

REQUIREMENT/BARRIER FUNCTION/RELEVANCE *SUITABLE MATERIALS/APPROACHES*

	transport/storage; prevents leaks or product exposure	- Reinforced composites (cellulose nanofibers)
Flexibility & Sealability	Facilitates multiple shapes (wraps, pouches) and effective sealing for freshness	- Thermoplastic polymers (PBS, PHA) - Plasticized proteins (casein + glycerol)
Transparency & Aesthetics	Enhances consumer perception of freshness and quality. Must balance light barrier to prevent oxidation	- Partially transparent polymers - Coatings with UV inhibitors - Protein/polysaccharide multilayers
Sustainability (Biodegrad./Compost.)	Decomposes in environmental or industrial composting, reduces waste & carbon footprint	- PLA, PHA, or starch-based packaging - Whey protein-starch blends - Cellulose-based materials
Recyclability	Integrates with existing recycling streams if recognized, supports circular economy.	- Bio-PE, Bio-PP (biodegradable substitutes) - PET with bio-derived monomers

REQUIREMENT/BARRIER FUNCTION/RELEVANCE

SUITABLE MATERIALS/APPROACHES

Sensory Integrity & Shelf Life	Retains flavor, aroma, and texture; curbs oxidation and off-flavors; prolongs product viability	- Active packaging with antioxidants/antimicrobials - Modified atmosphere packaging (MAP) - Vacuum-sealed packaging
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HDPE = High-density polyethylene; PP = Polypropylene; PLA = Polylactic acid; PHA = Polyhydroxyalkanoate; PBS = Polybutylene succinate; Bio-PE = Bio-based polyethylene; Bio-PP = Bio-based polypropylene.

Notably, the data in [Table 9.1](#) reveal a consistent pattern: biopolymers and related technologies offer multifunctionality—acting as both robust barriers and active agents—while upholding the circular-economy principles discussed earlier ([Sinha, 2024](#)). For instance, coupling biopolymer matrices with nanoparticle additives can simultaneously enhance mechanical strength and confer antimicrobial benefits ([Li et al., 2017](#); [Göksen et al., 2020](#)). By aligning these performance attributes with eco-friendly disposal paths, this approach tackles both sustainability imperatives and growing regulatory pressures to curb single-use plastics ([Singh et al., 2024](#)). Consequently, such integrated solutions exemplify a clear trajectory within the dairy sector: moving beyond conventional plastics toward biomaterials that satisfy safety, durability, and environmental concerns.

Moreover, this holistic view of packaging design—infused with advanced material science and ecological awareness—underscores the vital role of synergy between barrier performance and minimal ecological

impact. The dairy industry not only meets consumer and legislative demands for reduced plastic waste but also capitalizes on novel methods that extend shelf life and preserve product quality ([Dipierro et al., 2018](#); [Jafarzadeh et al., 2021b](#)). Ultimately, these convergent innovations point to a future-ready packaging paradigm, one that resonates with both brand values and market needs and paves the way for a more resilient, circular, and competitive market.

With this foundation established, the subsequent topic will delve deeper into the spectrum of biomaterials—from plant-based polysaccharides to dairy-derived proteins—and illustrate how each fulfills these stringent performance criteria while simultaneously adhering to sustainability goals. This next step highlights how the industry can move from incremental adjustments to a transformative embrace of eco-conscious materials, reshaping how milk, cheese, and other dairy commodities are packaged, perceived, and consumed in an increasingly responsible global marketplace.

9.6 CLASSIFICATION OF BIOMATERIALS FOR DAIRY PRODUCT PACKAGING

The search for sustainable dairy packaging has led researchers to explore a broad range of biomaterials that can replace conventional plastics while offering specific functional advantages. These materials can be broadly grouped into three categories: natural polymers of vegetal origin, dairy-based polymers, and synthetic biodegradable polymers. Each category presents unique advantages and limitations regarding barrier performance, mechanical properties, and sustainability.

[Table 9.2](#) provides a comprehensive overview of these groups, summarizing the key features, applications, advantages, and limitations of each material type. For instance, the table highlights how cellulose and its derivatives, despite offering good tensile strength and renewability, may require additional modifications to enhance their moisture barrier

performance. Similarly, it compares dairy-based polymers like casein and whey protein, emphasizing their excellent oxygen barrier properties yet noting the need for plasticizers to improve flexibility. The table also presents synthetic biodegradable polymers, such as PLA, PHA, and PBS, with detailed comparisons of their processability and end-use challenges.

As highlighted in [Table 9.2](#), the comparative analysis demonstrates that each biomaterial category offers unique benefits. For example, natural polymers from vegetal sources, while renewable and biodegradable, often require modifications to overcome moisture sensitivity. Dairy-based polymers such as casein and whey protein, derived from milk, are inherently compatible with food products but may need plasticizers to enhance flexibility. Synthetic biodegradable polymers like PLA, PHA, and PBS provide robust barrier properties and are industrially scalable, yet they face challenges related to moisture and thermal resistance. This integrated view, as presented in the table, underlines the importance of selecting the appropriate biomaterial based on the specific dairy product and its packaging requirements. The table further emphasizes that combining biomaterials with nanotechnology or other additives can lead to multifunctional packaging solutions, meeting both performance and sustainability targets.

The search for renewable materials in packaging production has become a key pillar of sustainability in the dairy industry. Major industry players are investing in the development of packaging composed of biodegradable and renewable-source polymers, aiming to reduce carbon footprints and minimize the environmental impact of conventional plastic packaging. Tetra Pak, a global leader in the sector, exemplifies this transition by developing packaging composed of up to 91% renewable materials, including Forest Stewardship Council™ (FSC™)-certified paper and plant-based plastics derived from sugarcane. This approach not only reduces dependency on fossil fuels but also enhances recyclability and material reuse, contributing to a more sustainable packaging production cycle ([Tetra Pak, 2023](#)).

TABLE 9.2 Overview of Biomaterials for Dairy Packaging [!\[\]\(528510d7a4b5a92b21675489a72c4b79_img.jpg\)](#)

CATEGORY	MATERIAL/SUBTYPE	SOURCE/EXTRACTION	KEY PROPERTIES
Natural Polymers of Vegetable Origin	Cellulose & Derivatives	Plant fibers, agricultural residues, bacterial cellulose	Moderate oxygen barrier, high tensile strength, compostable
	Starch & Derivatives	Corn, potato, cassava starch	High biodegradability, flexible yet plasticized, moderate barrier properties
	Starch-based biodegradable film with garlic extract	Sago starch	Enhanced antimicrobial and antioxidant properties, moisture retention
Synthetic Polymers of Marine Origin	Chitosan, Pectin, & Alginate	Chitosan: deacetylated chitin from crustaceans; Pectin: fruit wastes; Alginate: brown seaweed	Inherent antimicrobial activity; forms transparent films, moderate barrier properties

CATEGORY	MATERIAL/SUBTYPE	SOURCE/EXTRACTION	KEY PROPERTIES
Natural Polymers of Plant Origin	Cellulose	Derived from plant cell walls (e.g., wood, cotton)	High tensile strength, biodegradable, and UV-stable
	Additional Vegetal Polymers	Lignin (by-product of paper industry), soy protein isolate	Lignin: natural polymer and UV-protective protein: improves oxygen barrier, film-forming properties
Natural Polymers of Animal Origin	Gelatin	Collagen (bovine, porcine, fish)	High oxygen barrier, flexible, forming a biodegradable matrix

CATEGORY	MATERIAL/SUBTYPE	SOURCE/EXTRACTION	KEY PROPERTIES
Dairy-Based Polymers	Casein	Extracted from milk via coagulation	Excellent mechanical strength High oxygen barrier Highly transparent Biodegradable
	Whey Protein	By-product of cheese manufacturing	Good film-forming ability Inherent bioactivity Moderate thermal stability

CATEGORY	MATERIAL/SUBTYPE	SOURCE/EXTRACTION	KEY PROPERTIES
Synthetic Biodegradable Polymers			High clarity, good processability, compostable under industrial conditions
	Poly(lactic acid) (PLA)	Fermentation of sugars from corn, sugar beet	

CATEGORY	MATERIAL/SUBTYPE	SOURCE/EXTRACTION	KEY PROPERTIES
Biodegradable Polymers	Polyhydroxyalkanoates (PHA)	Produced by microbial fermentation from renewable substrates	100% biodegradable; comparable mechanical properties to conventional plastic
	Polybutylene Succinates (PBS)	Chemical synthesis from butanediol and succinic acid	Good tensile strength; moderate flexibility; compostable under controlled conditions
	Additional Polymers: PBAT & PCL	PBAT: chemical synthesis; PCL: thermoplastic polymer	PBAT: excellent flexibility and toughness; low melting point, good processability

This strategy aligns with recent scientific research on the use of sustainable biopolymers in the packaging industry. Studies indicate that replacing conventional plastics with biodegradable materials such as starch-

derived polymers, polyhydroxyalkanoates (PHA), and polylactic acid (PLA) can significantly reduce waste generation and environmental contamination ([Muižniece-Brasava et al., 2023](#)).

Furthermore, advancements in sustainable packaging design are optimizing mechanical performance and barrier properties against moisture and oxygen, ensuring product durability and food safety without compromising biodegradability ([Francis et al., 2024](#)). The recycling of these materials still faces technical and logistical challenges; however, initiatives such as the use of certified recycled polymers, recently adopted by Tetra Pak and Lactalis, demonstrate that innovative solutions are already being implemented on an industrial scale ([Feil et al., 2020](#)). Thus, the dairy industry is moving toward a scenario in which sustainable packaging is not just a trend but a regulatory and market-driven necessity. The positive impact of these solutions is evident not only in environmental conservation but also in brand valuation and consumer acceptance, as consumers are increasingly attentive to corporate sustainability practices ([Boz et al., 2020](#)).

9.7 NATURAL POLYMERS OF VEGETAL ORIGIN

9.7.1 Cellulose and Derivatives

Cellulose is the most abundant natural polymer and is available in several forms, such as microcrystalline cellulose, nanocellulose, and bacterial cellulose. In dairy packaging, cellulose-based films or laminates have been applied as coatings for cheese and milk containers, offering moderate oxygen barrier properties and a renewable alternative to synthetic plastics ([Plóska et al., 2024](#); [Jakobsen, 2008](#)).

Hydroxypropylmethyl cellulose (HPMC), a semi-synthetic cellulose derivative, has gained attention for biodegradable dairy packaging. Films incorporating nisin Z (0%, 5%, 10%, 15%, and 20% by weight), a natural

antimicrobial peptide, demonstrated effective inhibition of *Staphylococcus aureus*, *Listeria innocua*, and *Salmonella enterica Choleraesuis* in mozzarella cheese, extending shelf life while maintaining mechanical integrity ([Freitas et al., 2020](#)). The optimal concentration of nisin Z (10% by weight) showed the highest antimicrobial activity, reducing bacterial growth by approximately 0.5 log CFU/mL after eight days of refrigerated storage.

Biodegradable materials have gained prominence as sustainable alternatives to reduce the environmental impact of plastic waste. Their main advantages include renewability, good tensile strength, and compatibility with composting processes. However, these materials also present challenges, such as high sensitivity to moisture, which requires modifications, such as lamination with hydrophobic layers, to improve their water vapor barrier properties ([Figure 9.1](#)) ([Hamed et al., 2022](#)).

ADVANTAGES	LIMITATIONS
Renewable, good tensile strength, printable, and compatible with composting	High sensitivity to moisture necessitates modifications to enhance water vapor barrier properties

FIGURE 9.1 Advantages and limitations of biodegradable materials: benefits and challenges in sustainable application. [↩](#)

ADVANTAGES	LIMITATIONS
High biodegradability, low cost, and abundant availability	Lower mechanical and water resistance, requiring mixing or crosslinking

FIGURE 9.2 Advantages and limitations of biodegradable materials: benefits and challenges in sustainable application. [↩](#)

9.7.2 Starch and Its Derivatives

Starch extracted from sources such as corn, potato, or cassava is widely used to produce biodegradable films and coatings. These materials are especially suited for secondary packaging, such as internal liners for yogurt cups or wraps for cheese slices ([Ortega et al., 2017](#)). Chemical modifications (e.g., plasticization with glycerol) and blending with other biopolymers can improve flexibility and reduce hygroscopicity ([Mushtaq et al., 2018](#)).

The main advantages include high biodegradability, low cost, and wide availability. However, these materials have lower mechanical and water resistance compared to synthetic polymers, often requiring blending or crosslinking to improve their properties ([Figure 9.2](#)) ([Matheus et al., 2023](#)). Recent studies have also demonstrated that the reinforcement of starch-based bioplastics with additives such as dialdehyde starch, silica, and lemongrass fibers can significantly enhance mechanical strength, water barrier properties, and biodegradability, making these materials increasingly suitable for food packaging applications ([Oluwasina et al., 2021](#); [Abdullah et al., 2024](#)). Furthermore, blends of locust bean byproducts with potato starch have shown effectiveness in preserving fatty dairy products like cheese, maintaining product quality, and inhibiting microbial growth during storage ([Lopes et al., 2023](#)).

The development of starch-based biodegradable films reinforced with natural extracts, such as garlic extract, has proven effective in enhancing antimicrobial and antioxidant properties. [Gogineni et al. \(2024\)](#) developed a sago starch-based film enriched with garlic extract and applied it to paneer packaging. The active films improved moisture retention (41.04% vs. 50.25% in control), maintained pH stability (5.47 vs. 5.28), and reduced lipid oxidation and lipolysis (TBA: 0.544 mg/kg; FFA: 0.337%). These findings confirm the film's ability to control physicochemical deterioration during storage.

9.7.3 Chitosan, Pectin, and Alginate

Chitosan, derived from chitin found in crustacean shells, and pectin, obtained from fruit wastes, exhibit inherent antimicrobial properties. These biopolymers have been incorporated into edible coatings for cheeses and other dairy products to extend shelf life and improve safety ([Mushtaq et al., 2018](#); [Körge et al., 2020](#); [Hamed et al., 2022](#)). Recent studies have demonstrated the effectiveness of chitosan-based multilayer coatings containing bioactive compounds, such as nisin, for antimicrobial food packaging applications. A bilayer film composed of chitosan and cellulose, impregnated with nisin, exhibited strong antimicrobial properties against *Listeria monocytogenes*, a critical pathogen in dairy products. The study further highlighted that films with 1000 µg/mL of nisin completely inactivated the initial microbial load on ultra-filtered (UF) white cheese after 14 days of refrigerated storage, showing significant potential for cheese packaging ([Divsalar et al., 2018](#)).

Furthermore, a recent study explored the potential of pullulan-chitosan and pullulan-gelatin bilayer coatings as active antimicrobial systems for cheese preservation. These coatings, formulated with hydrolats from lemongrass and curry plant, exhibited strong antibacterial activity against *Staphylococcus aureus*. The study demonstrated that the bilayer coatings were effective both when applied before and after artificial contamination, highlighting their potential to reduce microbial proliferation throughout storage. The pullulan-chitosan formulation showed a biocidal effect, completely eliminating *S. aureus*, whereas the pullulan-gelatin formulation had a bacteriostatic effect, inhibiting growth over an extended period ([Erceg et al., 2024](#)). These findings underscore the viability of chitosan-based multilayer coatings in active dairy packaging, particularly for fresh and sliced cheese applications.

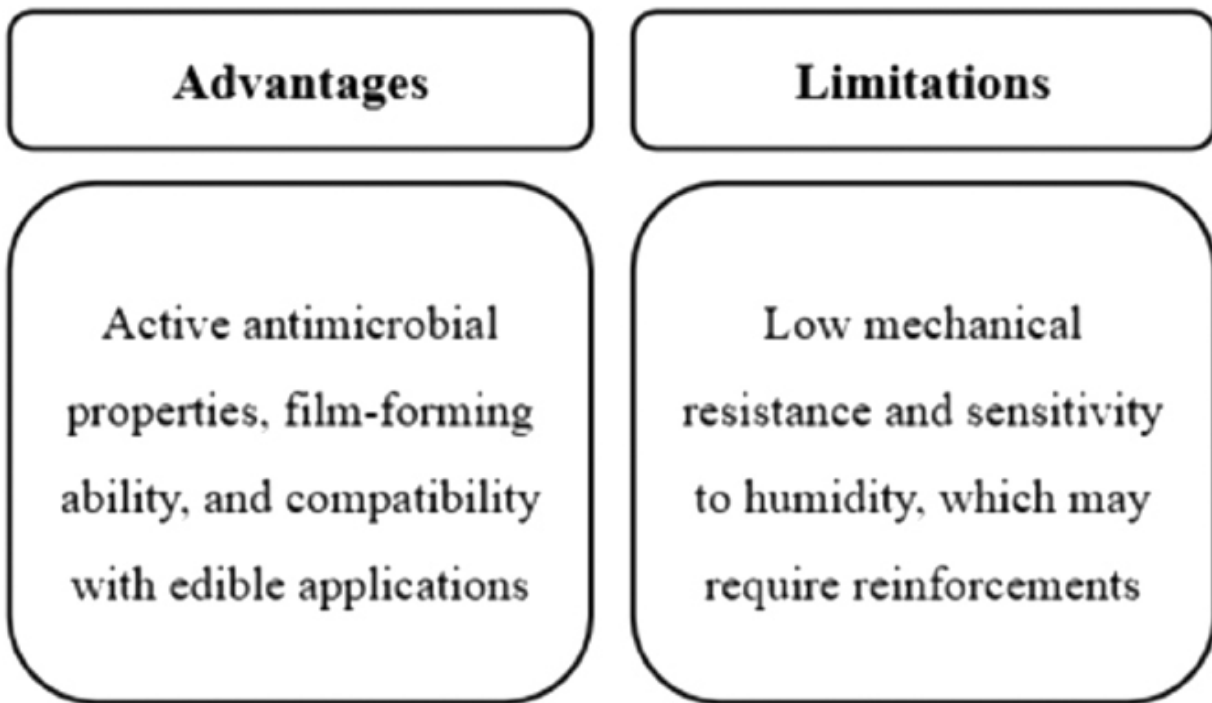


FIGURE 9.3 Advantages and limitations of biodegradable materials: benefits and challenges in sustainable application. [↗](#)

Recent studies have demonstrated the potential of alginate-based edible films and coatings in dairy packaging, particularly for cheese preservation. [Silva et al. \(2022\)](#) reported that alginate-maltodextrin-glycerol coatings incorporating bacteriocin-producing *Lactococcus* strains significantly reduced *Listeria monocytogenes* contamination and inhibited mesophilic bacteria growth during 10 days of refrigerated storage, while also minimizing moisture and weight loss in fresh cheeses. Additionally, [Papadopoulou et al. \(2022\)](#) demonstrated that sodium alginate edible films supplemented with functional LAB strains maintained high viable counts (above 6.35 log CFU/g) on cheese slices during refrigerated storage. These films contributed not only to microbial stability but also to improved sensory characteristics, particularly when combined with high-pressure processing. These findings highlight the suitability of alginate-based active packaging as a sustainable solution that enhances both safety and shelf life in dairy products. These materials have active antimicrobial properties, film-forming capacity, and compatibility with food applications. However,

they have limited mechanical strength and sensitivity to environmental humidity and may require reinforcements to improve their performance ([Figure 9.3](#)).

9.7.4 Additional Vegetal Polymers

Emerging research also focuses on lignin-based polymers and soy protein isolates. Lignin, a by-product of the paper industry, is being investigated for its potential as a reinforcement agent in biodegradable composites. Soy protein isolates, although less common in dairy packaging, can form films with good oxygen barrier properties and have been considered for niche applications such as high-end cheese packaging ([Reichert et al., 2020](#)).

9.8 NATURAL POLYMERS OF ANIMAL ORIGIN

Natural polymers derived from animal sources have gained increasing attention as sustainable alternatives to synthetic packaging materials. Among these, gelatin—a protein obtained from the partial hydrolysis of collagen—stands out due to its biodegradability, film-forming ability, and excellent oxygen barrier properties. While traditionally sourced from bovine and porcine skin, recent studies have explored fish-derived gelatin as a more sustainable option, reducing waste from the seafood industry while maintaining the functional properties required for food packaging.

One promising application involves gelatin films enriched with bioactive compounds, such as plant extracts, to enhance antioxidant and antimicrobial effects. [Salem et al. \(2021\)](#) developed biodegradable gelatin-based films using fish gelatin enriched with *Lepidium sativum* seed ethanol extract (LSE3), which demonstrated strong antioxidant activity (up to 97.65% DPPH radical scavenging) and antibacterial effects, particularly against *Bacillus cereus* (MIC = 75 µg/mL). When applied to Ricotta cheese, the

active films significantly reduced syneresis (by up to 40%), stabilized pH, inhibited bacterial growth, and limited lipid peroxidation (lowest MDA values after 6 days of storage). Additionally, the films helped preserve texture and color during refrigeration, confirming their effectiveness as active packaging. However, regarding mechanical performance, although the addition of LSE slightly increased film thickness and opacity, there were no statistically significant improvements in tensile strength or elongation at break compared to control films. The water solubility remained high (~45%), and the water vapor permeability was only marginally affected, indicating that gelatin films still require structural modification—such as cross-linking or blending with hydrophobic polymers—to effectively improve their mechanical robustness and moisture resistance for broader commercial applications ([Salem et al., 2021](#)). A recent study by [Cui et al. \(2024\)](#) explored another innovative approach by incorporating diacetyl, a natural antimicrobial metabolite produced by lactic acid bacteria, into gelatin-based edible films. These films exhibited strong antibacterial activity against *Listeria monocytogenes*, a major spoilage organism in cheese products. The mechanism of action involved damage to bacterial cell membranes and oxidative stress induction, effectively inhibiting bacterial growth. The study demonstrated that diacetyl-gelatin films not only extended the shelf life of Inner Mongolian cheese but also improved moisture stability by reducing weight loss by up to 15%, maintained pH balance within 4.6–4.8, preserved *cheese color* (higher *L* values), and reduced lipid oxidation, with malondialdehyde levels at 0.18 mg/kg compared to 0.37 mg/kg in untreated samples. Despite these advantages, the volatility and instability of diacetyl remain a challenge, requiring future research to enhance its controlled release and long-term effectiveness in biodegradable packaging materials ([Cui et al., 2024](#)). Gelatin-based films are biodegradable, renewable, and offer a high oxygen barrier, making them promising candidates for sustainable food packaging. In addition, their ability to incorporate bioactive compounds, such as plant extracts or natural antimicrobials, enhances their functionality, contributing to food safety and extending the shelf life of products ([Salem et al., 2021](#);

[Cui et al., 2025](#)). However, these films are sensitive to moisture, which can compromise their barrier properties during storage. Furthermore, although natural antimicrobials, such as diacetyl, aid in preservation, their stability and volatility still represent challenges that require further research to optimize the controlled release of these compounds ([Cui et al., 2025](#)).

9.9 DAIRY-BASED POLYMERS

9.9.1 Casein

Casein, the predominant milk protein, can be processed into films that exhibit excellent oxygen barrier properties and transparency. These films have been used in applications such as coating cheese surfaces and forming multilayer packaging systems to reduce oxidation and maintain flavor integrity ([Dipierro et al., 2018](#); [Costa et al., 2021](#)). Additionally, recent reviews have emphasized the potential of casein-based films reinforced with natural antioxidants and antimicrobial agents, such as plant extracts and essential oils, to improve microbial stability and extend the shelf life of dairy products. These composite films enhance functional properties, including water vapor barrier capacity, mechanical strength, and bioactivity, making them promising candidates for active dairy packaging applications ([Chaudhary et al., 2022](#)). Recent studies highlight the potential of casein-based films as a sustainable alternative in active food packaging. Advances in fabrication techniques, such as self-assembly and crosslinking, have enhanced the mechanical strength and moisture resistance of these films, making them more viable for dairy applications ([Gopalakrishnan et al., 2020](#)).

Materials with a high oxygen barrier, in addition to being renewable and biodegradable, represent a sustainable alternative for several applications. However, their sensitivity to moisture can compromise performance, requiring the use of plasticizers to improve flexibility and durability.

9.9.2 Whey Protein

Whey protein, a by-product of cheese manufacturing, is another valuable dairy polymer. It is used to produce edible films that provide a good barrier against oxygen and can be formulated with active agents (e.g., antimicrobial compounds) to enhance shelf life. Whey protein films are especially promising for packaging applications in which product safety and extended freshness are critical, such as in fresh cheese and yogurt coatings ([Ryder et al., 2018](#); [Mushtaq et al., 2018](#)). Recent studies have also highlighted the use of starch-based biodegradable films infused with natural extracts like garlic, demonstrating enhanced antimicrobial efficiency and oxidative stability.

Addressing the challenges of lipid oxidation and microbial spoilage in dairy products, researchers have explored whey protein films enhanced with bioactive compounds. [Mohammadian et al. \(2021\)](#) demonstrated that incorporating nettle (*Urtica dioica* L.) extract into whey protein isolate films increased DPPH radical scavenging activity from 32.64% to 73.23%, reduced water vapor permeability by nearly 30%, and improved tensile strength by up to 84%, all while significantly inhibiting the growth of *Escherichia coli* and *Staphylococcus aureus*. Similarly, [Arciello et al. \(2021\)](#) showed that whey protein films enriched with pecan nut shell extract achieved 67% DPPH inhibition, enhanced mechanical strength (from 3.2 MPa to 4.8 MPa), and provided effective antimicrobial activity against *Salmonella Typhimurium* and *Enterococcus faecalis*. These functionalized films represent a promising strategy to extend shelf life and improve the safety of dairy products.

[Aleksandrovas et al. \(2024\)](#) demonstrated that edible coatings based on acid whey protein concentrate (LAWPC) and pectin, when combined with lactic acid bacteria such as *Lactocaseibacillus paracasei* and *Lactobacillus helveticus*, effectively enhanced the preservation of Gouda cheese during 45 days of ripening and up to 205 days of storage. The coating enriched with *L. helveticus* notably reduced fungal counts and *Enterobacteriaceae spp.* on the cheese surface ($p \leq 0.001$), while maintaining quality attributes such as

pH (ranging from 5.54 to 5.64), water activity (final $a_w \approx 0.834\text{--}0.843$), and color stability ($\Delta E^* < 5$). Although weight loss increased in strain-treated samples, this was associated with enzymatic hydrolysis and moisture regulation. These findings confirm the potential of LAB-enriched whey protein coatings as a sustainable packaging alternative for extending shelf life and preserving cheese integrity. Emerging research has demonstrated that whey protein films, when combined with advanced crosslinking strategies and bioactive nanoparticles, can significantly improve mechanical durability and water resistance. These improvements address key challenges in dairy-based packaging, enabling whey protein films to be integrated into more demanding applications such as extended shelf-life dairy products ([Gopalakrishnan et al., 2020](#)).

9.9.3 Synthetic Biodegradable Polymers

9.9.3.1 Polylactic Acid (PLA)

PLA is produced from the fermentation of sugars derived from renewable sources like cornstarch or sugar beet. Widely used in dairy packaging for yogurt pots and milk containers, PLA offers high clarity and decent barrier properties; however, its performance under elevated temperatures and moisture can be limited ([Li et al., 2017](#); [Rejeesh & Anto, 2023](#)). [Dukalska et al. \(2011\)](#) demonstrated that PLA coatings, when combined with a silicon oxide (SiOx) barrier layer, improved the shelf life of soft cheese, reducing mass losses and microbial spoilage while maintaining sensory quality. The study also highlighted that reducing the thickness of PLA films did not significantly affect their protective performance, indicating potential for material optimization in sustainable dairy packaging applications ([Dukalska et al., 2011](#)). This material is a sustainable alternative because it is renewable, compostable under industrial conditions, and FDA-approved for food contact. However, its moderate moisture barrier and thermal limitations require modifications or combinations with other polymers to improve its performance.

9.9.3.2 Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHAs) are a family of biodegradable polyesters synthesized by various microorganisms under nutrient-limited conditions. These polymers stand out for their complete biodegradability, high thermal stability, and mechanical properties comparable to polypropylene and polyethylene, making them strong candidates to replace fossil-based plastics in food packaging ([Hamed et al., 2022](#)). While their use in dairy applications remains limited to pilot-scale and exploratory research, PHAs have been proposed for flexible packaging formats such as cheese wrappers, milk bottle linings, and yogurt containers, primarily due to their excellent oxygen barrier performance and water resistance. However, their widespread commercial adoption is hindered by high production costs, limited microbial productivity, and the need for efficient downstream processing technologies ([Hamed et al., 2022](#)). Recent studies have sought to overcome these limitations by using dairy by-products, such as cheese whey and ricotta whey, as substrates for PHA synthesis. [Wang et al. \(2021\)](#) demonstrated the feasibility of producing PHBV from delactosed cheese permeate using *Haloferax mediterranei*, achieving yields of 0.2 g PHBV per g of lactose and an overall process efficiency of 87%, with a projected production of 9700 tons/year at an industrial scale. Similarly, [Raho et al. \(2020\)](#) achieved 1.18 g/L of PHBV from ricotta whey, highlighting the potential of this substrate for sustainable biopolymer production. [Tripathi et al. \(2021\)](#) reviewed multiple applications of dairy-derived PHAs and emphasized their promising oxygen and moisture barrier properties, as well as compatibility with bioactive additives for active food packaging. Together, these findings reinforce the viability of PHAs as a sustainable alternative for dairy packaging, especially when integrated with circular economy strategies that valorize dairy waste streams.

9.9.3.3 Polybutylene Succinates (PBS)

PBS is an aliphatic polyester that has emerged as a promising substitute for conventional polyethylene ([Shin et al., 2024](#)). In dairy packaging, PBS is

explored for use in containers and flexible films, offering good mechanical properties and biodegradability under composting conditions ([Plóska et al., 2024](#)). This material has good tensile strength, flexibility, and compostability, making it a sustainable option. However, optimizing processing parameters is essential to improve its barrier properties, especially against moisture.

9.9.3.4 Additional Synthetic Biodegradable Polymers

Recent advancements have highlighted the potential of synthetic biodegradable polymers such as polybutylene adipate-co-terephthalate (PBAT) and polycaprolactone (PCL) in dairy packaging. PBAT is often blended with starch or polylactic acid (PLA) to improve flexibility and mechanical strength. For instance, PLA/PBAT-based films exhibit tensile strength around 9.4 MPa and elongation at break exceeding 500%, ensuring high flexibility suitable for packaging soft cheeses and dairy beverages ([Myalenko & Fedotova, 2023](#)). These films have also demonstrated long-term compostability, maintaining structural integrity for up to 365 days under composting conditions. PCL, known for its low melting point and excellent compatibility with bioactive and natural polymers, has been successfully applied in multilayer films used for packaging dairy products, particularly white cheese. These composites enhance structural durability and enable the incorporation of functional additives such as antioxidants or antimicrobials, improving product safety and shelf life ([Oney-Montalvo et al., 2024](#)). Broader reviews recognize PBAT and PCL as promising materials due to their biodegradability, favorable barrier properties, and thermal stability, making them strong candidates for high-moisture dairy applications such as cheese, yogurt, and fermented beverages ([Singh et al., 2024](#)).

9.9.3.5 Multilayer Films

Multilayer films combining biodegradable and synthetic layers have demonstrated considerable potential in dairy packaging due to their ability

to balance barrier properties and mechanical integrity. These films are particularly useful in maintaining cheese quality during storage by controlling gas exchange and moisture loss. [Costa et al. \(2016\)](#) investigated the impact of multilayer films on the packaging of Canestrato di Moliterno cheese and observed that high-barrier multilayer films preserved sensory attributes and significantly delayed mold growth. Cheeses stored for 180 days in films with ethylene vinyl alcohol (EVOH) layers maintained lower microbial counts and higher consumer acceptance scores compared to conventional packaging. [Renoldi et al. \(2024\)](#) compared conventional multilayer packaging (e.g., MultiMAP and MultiVAC) with recyclable mono-material alternatives in semi-hard cheeses. Multilayer films offered better oxygen and moisture barrier performance, reducing lipid oxidation by up to 28% and preserving texture and color parameters ($\Delta E < 2.5$) over 35 days of storage. These results underscore the continued relevance of multilayer systems for products requiring extended shelf life and quality protection. In a recent study, [Rofeal and Abdelmalek \(2023\)](#) developed bioactive multilayer films based on edible gelatin/xanthan gels crosslinked with *Echinacea purpurea* extract and applied them to Ricotta cheese. The active multilayer system achieved a 4-log reduction in total viable count, maintained stable pH levels (~ 6.3) over 15 days, and effectively preserved color and texture parameters. This highlights the potential of combining bio-based and functional materials to develop high-performance, multilayer films for dairy preservation.

The adoption of these three groups of biomaterial—vegetal-origin polymers, dairy-based polymers, and synthetic biodegradable polymers—can significantly contribute to reducing conventional plastic use. By leveraging renewable feedstocks and advanced processing techniques, the dairy industry can achieve packaging solutions that not only meet performance criteria such as mechanical strength and barrier efficiency but also address environmental imperatives through biodegradability and recyclability ([Sinha, 2024](#); [Singh et al., 2024](#)).

9.10 APPLICATIONS OF SUSTAINABLE BIOMATERIALS FOR DAIRY PACKAGING

The rapid evolution of sustainable biomaterials has not only provided alternatives to conventional petroleum-based plastics but has also enabled the development of packaging solutions that enhance product safety, shelf life, and environmental performance. This section presents an in-depth analysis of industrial applications of these biomaterials across different dairy product categories. The discussion is organized into four subtopics: packaging for cheeses and derivatives, packaging for milks and dairy beverages, packaging for yogurts and dairy desserts, and an overview of recent case studies and pilot-scale research.

9.10.1 Overview of Industrial Applications

9.10.1.1 Packaging for Cheeses and Derivatives

Cheese packaging must offer high moisture and oxygen barrier properties while also ensuring antimicrobial protection to prevent spoilage. Traditional materials such as polyethylene (PE) and polyvinylidene chloride (PVDC) have dominated the market, but biodegradable alternatives are now under study and commercial use ([Dipierro et al., 2018](#)). Additionally, the incorporation of active and intelligent packaging solutions in cheese packaging has been gaining attention, aiming to monitor and extend product shelf life while reducing spoilage losses.

9.10.1.2 Industrial Applications of Sustainable Cheese Packaging

Recent advances in sustainable cheese packaging have demonstrated increasing relevance for industrial applications, especially those involving bio-based and biodegradable materials. For instance, edible films made from whey protein concentrate combined with spirulina were applied to kefalotyri cheese during refrigerated storage. After two months, these films

effectively preserved the cheese's volatile profile, demonstrating minimal impact on sensory attributes such as aroma and flavor, and confirming their potential for use in industrial dairy packaging systems. Similarly, biodegradable cling films from renewable and circular sources—specifically R-BP1 and R-BP2—were tested on semi-hard cheeses for 14 days at 5°C. Analytical techniques, including image analysis, electronic nose profiling, and sensory evaluation, showed that these films maintained cheese appearance and odor comparably or superiorly to conventional LDPE and PVC films. Notably, R-BP1 achieved the highest consumer acceptability scores for both visual and olfactory parameters. Further industrial potential is illustrated by the application of polylactic acid (PLA) films coated with silicon oxide (SiO_x), which provide superior oxygen and moisture barrier properties compared to conventional PVDC-based materials. According to Jakobsen et al., these coatings support cheese ripening and shelf-life extension while offering compostability at end-of-life, thus aligning with sustainability targets within the food packaging sector. A systematic review of over 400 scientific articles and 2,200 patents revealed that the most adopted strategies in sustainable cheese packaging involve the use of active, vacuum, and modified atmosphere systems—often coupled with biodegradable polymers, particularly bio-based plastics. Academic publications have shown a growing emphasis on extending shelf life via active packaging technologies, while patents continue to prioritize biodegradability. The trend suggests a progressive industrial shift toward intelligent packaging systems with embedded sensors and functional responsiveness to food quality parameters. This perspective is further reinforced by global evaluations of preservation technologies in the cheese sector. Among the innovations implemented at an industrial level are high-pressure processing, vacuum sealing, and active films incorporating natural antimicrobial compounds. These methods are not only effective in prolonging cheese shelf life but also respond to increasing consumer expectations for minimally processed foods with clean labeling and reduced environmental impact. The innovations described herein reflect the dairy industry's growing commitment to combining technical performance with

sustainability, advancing the transition toward a more ecologically responsible production chain.

9.10.1.3 Emerging Technologies in Cheese Packaging

Among the most promising advances in sustainable cheese packaging, two research fronts have emerged: edible coatings enriched with natural antimicrobials and nanocomposite-enhanced films. The first approach explores bio-based edible coatings composed of polysaccharides, proteins, or cellulose derivatives combined with plant-derived antimicrobial agents. For instance, cellulose-based films containing propolis and hesperidin were applied to white cheese stored at 4°C and achieved microbial inhibition rates exceeding 50% for *Escherichia coli* and *Staphylococcus aureus*, without altering pH, texture, or sensory characteristics throughout the storage period ([Yildirim & Ates, 2022](#)). Similarly, [Mushtaq et al. \(2018\)](#) demonstrated that zein-based films enriched with pomegranate peel extract reduced lipid oxidation by 35.6% and microbial growth by up to 2 log CFU/g in treated cheese samples, while being fully biodegradable. Additional reviews confirm that coatings formulated with chitosan, whey protein, or alginate, when combined with essential oils such as oregano or rosemary, not only inhibit microbial growth but also improve oxidative stability, with lipid oxidation reductions reported between 30% and 45%, depending on the matrix and storage time ([Costa et al., 2018](#)). These formulations are particularly attractive due to their low environmental impact and their compatibility with soft and semi-hard cheeses, offering natural preservation methods aligned with clean-label demands. In parallel, nanocomposite-enhanced films represent a second innovative direction. These materials incorporate nano-reinforcements such as cellulose nanofibers or halloysite nanotubes to improve mechanical performance and barrier properties. [Giannakas et al. \(2023\)](#) developed a sodium alginate-based hydrogel film loaded with thymol-functionalized halloysite nanohybrids and tested it as an active coating for Tsalafouti spreadable cheese. After nine days of refrigerated storage at 8°C, microbial counts of

mesophilic bacteria in the coated samples decreased by over 1 log CFU/g compared to uncoated controls. The film also improved oxygen barrier performance by 31.5% and increased tensile strength by 42.1%, while showing antioxidant activity above 50% via DPPH radical scavenging. These results were statistically significant ($p < 0.05$), with an effect size of 0.89 and $\eta^2 = 0.44$, indicating robust and meaningful improvements in preservation capacity.

Furthermore, a recent review by [Lima et al. \(2021\)](#) highlights the incorporation of essential oils, peptides, and metallic nanoparticles into biopolymer matrices as a pathway to broaden antimicrobial spectra while maintaining sensory integrity. Although these systems exhibit great laboratory-scale potential, the authors emphasize that the path to commercialization requires overcoming regulatory hurdles, cost optimization, and consumer perception challenges, particularly for nanomaterials. Taken together, these two approaches—bioactive edible coatings and bio-nanocomposites—underscore the ongoing evolution in cheese packaging technologies, aiming to reconcile food safety, shelf-life extension, and environmental sustainability. While promising, their full-scale industrial application will depend on continued innovation, regulatory clarity, and sustainable production strategies.

9.10.2 Packaging for Milks and Dairy Beverages

Packaging for milk and dairy beverages must meet strict functional requirements, including sterility, high barrier properties against light and gases, mechanical resilience, and suitability for cold storage. Traditionally, materials such as multilayered beverage cartons and HDPE or PET bottles have dominated the sector. However, growing concern over plastic waste and carbon emissions has driven the development of packaging aligned with sustainability principles, including recyclability, biodegradability, and reduced environmental footprint. Recent regulatory pressures, such as the European Union's Packaging and Packaging Waste Regulation (PPWR), have further accelerated innovation in this area. According to [Klein et al.](#)

[\(2025\)](#), a comparative sustainability assessment of dairy packaging in the DACH region showed that cartons with a high share of renewable content and recyclability had the lowest climate impact (approximately 70 kg CO₂-eq per 1,000 liters of milk) and the highest circularity potential. Similarly, [Rejeesh and Anto \(2023\)](#) emphasize that the integration of active, intelligent, and biodegradable packaging technologies is crucial to improve shelf life while reducing ecological burden.

9.10.2.1 Sustainable Packaging Solutions in the Dairy Industry

Recent sustainable innovations in dairy packaging focus on two primary strategies: enhancing traditional formats (such as cartons) with renewable materials and recyclability, and developing new biodegradable polymer alternatives like PLA-based containers. Tetra Pak and SIG Combibloc have introduced renewable-based beverage cartons made with biopolyethylene derived from sugarcane ethanol, promoting fully recyclable aseptic packaging formats. These efforts align with circular economy models and are supported by environmental assessments indicating lower carbon emissions and non-renewable energy use compared to conventional multilayer plastics ([Rejeesh & Anto, 2023](#); [Klein et al., 2025](#)).

Complementarily, biodegradable packaging solutions using polylactic acid (PLA) have been investigated for fermented dairy products. In an experiment evaluating the storage stability of whole milk yoghurt, [Mikloskova et al. \(2021\)](#) compared PLA and polystyrene (PS) cups under refrigerated conditions for 42 days. The PLA cups maintained consistent pH, water content, and viscosity, while protecting against light-induced degradation. Headspace oxygen concentrations in PLA cups were slightly lower than in PS, and peroxide values remained lower under light exposure, indicating reduced lipid oxidation—a key indicator of product freshness. Gallego-[Schmid et al. \(2022\)](#) contributed further by conducting a life cycle assessment (LCA) of milk packaging formats in the UK. Their study found that HDPE bottles produced 51% more greenhouse gas emissions per liter of milk than returnable glass bottles when reuse logistics were optimized.

The analysis also showed that milk pouches had the lowest environmental impact, though they faced limitations in consumer acceptance and mechanical durability.

Meanwhile, [Madden et al. \(2023\)](#) examined the recovery rate of packaging-grade plastic from milk bottles in Australia. The study showed that only 36% of HDPE used in milk bottles is currently recovered for high-quality recycling. However, with system-level changes—such as improving collection schemes, consumer sorting behavior, and removing label contaminants—recovery rates could rise to 61%, substantially reducing landfill volume and increasing circularity. Altogether, these findings highlight that sustainable packaging for milk and dairy beverages is multifaceted, involving renewable material adoption, performance optimization of bioplastics, infrastructure upgrades for recycling, and regulatory support. Moving forward, scalable and context-adapted solutions that ensure food safety, material efficiency, and environmental responsibility will be critical to achieving a sustainable dairy supply chain.

9.10.2.2 Challenges and Potential of Biopolymer-Based Milk Packaging

The development of biopolymer-based packaging for milk and dairy beverages represents a promising step toward sustainability in the dairy sector. However, its industrial application still faces significant challenges, especially regarding mechanical performance, moisture sensitivity, compatibility with dairy-specific packaging needs, and consumer acceptance. Milk is particularly demanding in terms of packaging functionality due to its high water content, susceptibility to light and oxidation, and its requirement for sterility and structural integrity throughout cold-chain distribution. Proteins from dairy industry by-products, especially whey and casein, are increasingly used to produce films and coatings. [Gerna et al. \(2023\)](#) highlight that milk protein-based films exhibit good oxygen barrier properties due to their dense molecular structure; however, they remain highly sensitive to moisture. Plasticizers

such as glycerol and sorbitol improve film flexibility but also increase water permeability, compromising their functionality for high-moisture products like milk. Attempts to reinforce these films with nanoparticles or crosslinking agents have shown improved resistance but require more toxicological validation before widespread use in dairy packaging. [Jakobsen \(2008\)](#) further stresses that biopolymers in dairy applications must meet strict hygiene and functional demands, including sealing properties, low oxygen transmission rate (OTR), and compatibility with modified atmosphere packaging (MAP). For example, some biodegradable films made from starch or cellulose derivatives may be suitable for short-shelf-life dairy products but fail under pasteurization conditions or long-term storage. In terms of consumer perception, [Cammarelle et al. \(2021\)](#) showed that 74% of Italian consumers surveyed expressed willingness to purchase milk packaged in biodegradable bottles derived from dairy or plant-based waste. However, acceptance was influenced by perceived quality, price expectations, and trust in labeling. The study used a structural equation model and revealed that attitudes and perceived behavioral control were the most significant predictors of purchasing intention. Emerging intelligent biopolymer packaging technologies also show potential in dairy applications. A preprint by [Devi et al. \(2023\)](#) described a gelatin-alginate-based film incorporating onion peel extract, which changes color in response to pH variation and can serve as a visual freshness indicator for milk. The developed film showed distinct color transitions from purple to yellow over a pH range of 6.5–3.5 and retained acceptable mechanical and optical properties for commercial consideration.

Finally, [Garavand et al. \(2022\)](#) emphasize that the scalability of these biopolymers remains limited by processing incompatibility with standard dairy filling lines, as well as by cost and regulatory uncertainty. Even when materials show strong performance in the lab, transitioning to large-scale production with consistent quality and regulatory compliance is still a major hurdle. Their review of milk protein-based packaging concluded that while structural enhancements using nanomaterials and functional additives are promising, the full integration of such systems into the dairy industry will

require technological adaptation and systemic changes across the supply chain. Together, these findings underscore the technical potential of biopolymer-based materials for milk packaging but also highlight the need for continued multidisciplinary research bridging materials science, food engineering, and consumer behavior.

9.10.3 Packaging for Yogurts and Dairy Desserts

Yogurt and dairy dessert packaging is undergoing a notable transformation as the industry moves toward circular economy solutions. Biodegradable materials such as polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), and chitosan-based hydrogels have shown promising functional and environmental performance. [Mikloskova et al. \(2021\)](#) compared PLA and polystyrene (PS) cups for plain stirred whole milk yogurt and observed stable water content and viscosity over 42 days at $2.4 \pm 0.4^{\circ}\text{C}$. PLA cups better preserved headspace oxygen levels and prevented light-induced degradation, indicating their suitability for refrigerated dairy applications, despite some loss of optical clarity.

Additionally, Karydis-[Messinis et al. \(2024\)](#) developed edible membranes using chitosan and casein, capable of forming films with zero oxygen permeability and high tensile strength (up to 5.2 MPa). These films, derived from dairy proteins and made from dairy waste, offer viable alternatives for dairy dessert packaging while enhancing barrier properties and biodegradability.

9.10.3.1 Commercialized Sustainable Yogurt Packaging

A market analysis by [Kostic and Hoffmann \(2022\)](#), surveying 150 yogurt and dairy dessert packages from German supermarkets, showed a dominance of PS and PP cups but highlighted the absence of PLA in most commercial applications. The study emphasizes opportunities for PLA integration, especially where packaging weight and filling efficiency are critical. Despite limited market penetration, companies like Nestlé Chile, in partnership with Emsur, have launched PLA-based yogurt cups with

compostable labels, meeting EU compostability standards while retaining oxygen barrier functions ([Rejeesh & Anto, 2023](#)). These containers are designed for industrial composting and maintain mechanical performance compatible with dairy production lines. Roclayer has also introduced fully compostable yogurt packaging utilizing multilayer biopolymer blends. These cups demonstrated comparable rigidity and moisture barrier properties to conventional PP containers, further supporting the viability of industrial-scale bio-based packaging.

9.10.3.2 Intelligent and Active Packaging for Dairy Desserts

The integration of smart and active components into dairy dessert packaging aims to enhance food safety, shelf life, and consumer engagement. [Francis et al. \(2024\)](#) reviewed sustainable packaging materials for probiotic fermented products such as yogurts and kefir, emphasizing the role of bio-indicators and antimicrobial agents in intelligent systems. They underline regulatory and technical challenges, particularly for probiotics that require controlled microenvironments. [Jafarzadeh et al. \(2021a\)](#) demonstrated gelatin-based films enriched with red cabbage extract, which underwent visible color transitions from purple to yellow as pH decreased from 7 to 2—an effective indicator of microbial spoilage. These films are promising for yogurt applications, where acidification is a key spoilage mechanism.

Additionally, edible coatings based on chitosan and essential oils (e.g., oregano, cinnamon) have shown antimicrobial effects against *E. coli*, *Listeria monocytogenes*, and *Staphylococcus aureus*, extending the shelf life of high-protein dairy desserts by up to seven days, depending on the matrix and formulation ([Hamed et al., 2022](#)). Finally, [Rudakova et al. \(2024\)](#) explored the influence of packaging conditions on the structural integrity of dairy desserts. Their study revealed that packaging filled at temperatures above 60°C altered viscosity and gel strength, reinforcing the importance of material compatibility and heat resistance in dessert applications.

9.10.4 Case Studies and Recent Research

9.10.4.1 Industrial Trials of Biodegradable Dairy Packaging

Recent industrial efforts have focused on testing biodegradable materials such as PLA and its composites in real dairy packaging environments. These trials provide critical insights into both the functional viability and limitations of these sustainable alternatives.

[Mikloskova et al. \(2021\)](#) evaluated plain stirred yogurt (3.7% fat) stored in PLA and polystyrene (PS) cups for 42 days under commercial refrigeration. While water content, viscosity, and microbial quality remained stable, PLA packaging demonstrated better protection against oxygen ingress compared to PS. Notably, PLA's opaqueness effectively prevented light-induced degradation, such as vitamin loss and lipid oxidation, enhancing yogurt shelf life under light exposure. However, slight haze formation in PLA cups was observed, which may affect consumer perception.

In another real-world trial, Muižniece-[Brasava et al. \(2023\)](#) tested Ceramis® PLA-SiOx multilayer films on soft cheese (*Kleo*) in an industrial setting. The packaging extended the product shelf life to 10 days, but this was deemed insufficient for broader commercial application. The study emphasized the need for enhanced oxygen and moisture barrier properties, particularly for highly perishable dairy products, and pointed to the promising integration of antimicrobial or nanocomposite layers to improve functionality. [Zhao et al. \(2018\)](#) contributed further by evaluating PLA, PBAT, and PBS packaging in direct contact with milk and food simulants to assess migration levels of potential contaminants. Migration was minimal in actual milk; however, some simulants exceeded EU limits for specific compounds such as triethylene glycol. These findings underline the importance of comprehensive risk assessments before industrial deployment.

Additionally, [Ščetar et al. \(2019\)](#) provided an industrial perspective by reviewing key technical challenges in implementing biodegradable

packaging across the dairy supply chain. These include heat resistance, compatibility with modified atmosphere packaging (MAP), and maintaining mechanical integrity under cold storage. The authors noted that while lab-scale results are encouraging, successful upscaling depends on harmonized regulations and advances in production technology. Collectively, these studies show that biodegradable materials like PLA and its nanocomposites are reaching industrial maturity. Nevertheless, technical hurdles related to barrier performance, process integration, and regulatory approval remain. Continued collaboration between industry, researchers, and policymakers is essential to drive the commercial adoption of sustainable packaging in the dairy sector.

9.11 EMERGING TECHNOLOGIES FOR SUSTAINABLE PACKAGING

9.11.1 Nanotechnology Applied to Biopolymers

Nanotechnology has revolutionized the development of sustainable dairy packaging by improving the mechanical, barrier, and antimicrobial properties of biopolymer-based materials. The incorporation of nanoscale additives enhances structural integrity, reduces permeability, and extends the shelf life of dairy products, aligning with the industry's sustainability goals ([Sinha, 2024](#); [Singh et al., 2024](#)).

One of the most significant applications of nanotechnology in sustainable dairy packaging is nanocellulose-based reinforcements. Nanofibrillated cellulose (NFC) and cellulose nanocrystals (CNC) have been widely explored as biodegradable fillers for improving the mechanical properties and gas barrier performance of biopolymeric films. These materials, derived from renewable sources, provide excellent tensile strength while reducing oxygen and moisture permeability, making them highly suitable for dairy product packaging ([Göksen et al., 2020](#)). Research indicates that

nanocellulose can be effectively integrated into biopolymers such as polylactic acid (PLA) and starch-based films, enhancing their structural stability without compromising biodegradability ([Jafarzadeh et al., 2021a](#)). Moreover, CNCs have been demonstrated to improve heat resistance, an essential property for dairy packaging subjected to thermal processing ([Reichert et al., 2020](#)).

Another critical advancement in nanotechnology is the use of antimicrobial nanoparticles to prevent spoilage and microbial contamination in dairy packaging. Silver nanoparticles (AgNPs), titanium dioxide (TiO₂), and zinc oxide (ZnO) are commonly incorporated into biodegradable films to inhibit bacterial growth. Studies demonstrate that AgNPs exhibit strong antimicrobial efficacy against spoilage microorganisms found in dairy products, thereby improving food safety ([Ortega et al., 2017](#)). However, the use of metal oxide nanoparticles has raised regulatory concerns regarding migration levels into food products. The European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have imposed strict guidelines to evaluate their safety in food-contact applications ([Reichert et al., 2020](#)). Furthermore, recent studies suggest that chitosan-based nanocomposites may offer a promising alternative to synthetic antimicrobial nanoparticles, reducing concerns related to toxicity while maintaining high antibacterial efficiency ([Singh et al., 2024](#)).

Nanotechnology-based emulsions have also been developed to enhance the dispersion and stability of bioactive compounds in biodegradable films. Lipid-based nanoemulsions containing natural antimicrobials, such as essential oils and plant extracts, have shown promising results in improving food safety and extending the shelf life of dairy products ([Perveen et al., 2023](#)). These nanoemulsions enhance the controlled release of antimicrobial agents, allowing for prolonged activity and improved effectiveness against spoilage bacteria. A study by [Patil et al. \(2024\)](#) highlighted the potential of nanotechnology in hybrid biopolymer matrices, integrating nano-sized fillers to enhance the mechanical and barrier properties of dairy packaging films. The study demonstrated that the incorporation of nano-silica into

polysaccharide-based films significantly improves water vapor resistance, a critical factor in dairy product preservation.

9.11.2 Hybrid Biomaterials in Sustainable Dairy Packaging

Hybrid biomaterials, which integrate biodegradable polymers with nanomaterials, have emerged as a cutting-edge solution for enhancing the properties of sustainable dairy packaging. These materials combine the flexibility and biodegradability of natural polymers with the strength and barrier properties of nanostructured additives, offering superior performance in food packaging applications ([Pathiraja & Munaweera, 2024](#)).

One promising example is chitosan-based hybrid biomaterials, which exhibit both antibacterial properties and high oxygen barrier efficiency, making them suitable for dairy product preservation. Additionally, bio-nanocomposites composed of PLA reinforced with nanocellulose have demonstrated enhanced durability, mechanical strength, and moisture resistance, crucial for extending the shelf life of perishable dairy products ([Shukla, 2012](#)). Furthermore, hybrid biomaterials incorporating montmorillonite (MMT) and graphene oxide have been investigated for their potential to enhance the thermal stability and mechanical properties of dairy packaging. These nanocomposites exhibit excellent resistance to moisture, thereby reducing the risk of microbial growth and improving product safety ([Sinha, 2024](#)).

9.11.3 Polyhydroxyalkanoates (PHA) from Dairy Waste as Biodegradable Packaging

Recent advancements have explored the potential of polyhydroxyalkanoates (PHA), biodegradable polymers synthesized by microorganisms, as an eco-friendly alternative to petroleum-based plastics. The study by [Patil et al. \(2024\)](#) demonstrated that dairy industry waste, such as whey, can be used as a feedstock for PHA production through microbial fermentation. The research highlighted that *Ralstonia eutropha* efficiently converts dairy waste

into PHA, yielding bioplastics with properties comparable to conventional plastics while promoting circular economy principles in dairy packaging ([Patil et al., 2024](#)).

9.11.4 Active and Intelligent Packaging for Dairy Products

Recent advancements in packaging technologies have introduced novel solutions to extend shelf life, improve food safety, and enhance product quality, particularly in the dairy sector. Among these, smart packaging systems have gained attention as they integrate active and intelligent functionalities to enhance cheese preservation. Active packaging solutions include antimicrobial films, antioxidant releasers, and self-cleaning coatings, which contribute to controlling microbial growth and oxidative deterioration during storage. Meanwhile, intelligent packaging systems, such as freshness indicators and ripening sensors, offer real-time monitoring of product quality, aiding in food safety and waste reduction ([Deshwal & Panjagari, 2024](#)). Despite their potential, the large-scale application of smart packaging in the dairy industry still faces challenges related to cost, regulatory approvals, and consumer acceptance. A study by Soltani [Firouz et al. \(2021\)](#) discusses advancements in intelligent packaging for dairy applications, including biosensors for monitoring microbial contamination and freshness indicators that change color based on pH shifts. These technologies improve transparency and safety for consumers while reducing food waste. [Karaman et al. \(2015\)](#) highlight that absorbers and scavengers play a crucial role in dairy packaging by minimizing oxygen and moisture exposure, which are primary factors in spoilage. For example, they report that packaging materials incorporating oxygen scavengers can reduce oxygen concentrations inside sealed containers to below 0.01%, significantly slowing down oxidative reactions and microbial growth. Similarly, moisture barriers are essential in products like dried milk powders, where even slight humidity can lead to clumping and nutritional degradation. Therefore, selecting materials with both oxygen and water vapor transmission rates below 1 cc/m²/day and 1 g/m²/day, respectively, is

recommended for high-quality preservation. The integration of smart packaging technologies in the dairy industry is rapidly evolving to enhance food safety, traceability, and consumer engagement. One of the most promising advancements is the incorporation of nano-based freshness indicators, which enable real-time monitoring of dairy product quality by detecting biochemical changes that signal spoilage. These biosensor-based nanomaterials improve food safety by providing immediate feedback on product freshness, reducing food waste, and enhancing consumer confidence ([Bhatlawande et al., 2024](#)). Additionally, the adoption of QR code-enabled smart packaging is gaining traction, allowing instant access to critical product information, such as origin, nutritional data, and supply chain traceability. This Internet of Things (IoT)-based technology, combined with printed sensors and unique item-level identifiers, is a key innovation in the transition toward a circular economy, improving transparency and supply chain efficiency ([Gligoric et al., 2019](#)).

The application of nanotechnology, hybrid biomaterials, and biodegradable polyhydroxyalkanoates (PHA) in dairy product preservation marks a transformative shift toward sustainable packaging solutions. These advancements contribute to reducing carbon footprints, improving product safety, and fostering circular economy practices in the dairy industry. Future research should focus on optimizing hybrid biomaterial formulations, expanding industrial composting infrastructure, and ensuring regulatory compliance to accelerate the large-scale adoption of these sustainable packaging solutions ([Table 9.3](#)).

TABLE 9.3 Emerging Technologies in Sustainable Dairy Packaging [!\[\]\(ba1b80118482ccef74a5d718ca4d7242_img.jpg\)](#)

TECHNOLOGY	DESCRIPTION	KEY BENEFITS	CHALLENGES	RISKS
Nanocellulose-based Materials	Incorporation of nanocellulose into biopolymers for improved mechanical	Enhanced strength, reduced oxygen/moisture	Cost of production, regulatory concerns	Environmental impact, potential allergenicity

TECHNOLOGY	DESCRIPTION	KEY BENEFITS	CHALLENGES	REFERENCES
	strength and barrier properties	permeability, biodegradable		
Antimicrobial Nanoparticles	Use of AgNPs, ZnO, and TiO2 nanoparticles in dairy packaging to inhibit microbial growth	Increased shelf life, reduced spoilage, food safety enhancement	Potential toxicity, regulatory limitations	Garcia et al., 2018 Rahman et al., 2020
Hybrid Biomaterials	Combination of biodegradable polymers with nanomaterials for superior performance	Improved strength, moisture resistance, and oxygen barrier	Processing complexity, cost factors	Ferreira et al., 2019 Liu et al., 2021
PHA-based Packaging	Biodegradable polyhydroxyalkanoates derived from dairy waste	Circular economy integration, eco-friendly alternative to plastics	High production cost, limited large-scale application	
Controlled Release Packaging	Active packaging with antimicrobial and antioxidant release systems	Real-time food protection, spoilage prevention	Regulatory approval, stability of active agents	Patel et al., 2017 Chen et al., 2020
Intelligent Packaging Sensors	pH-sensitive indicators, freshness sensors, and biosensors for monitoring dairy product quality	Real-time quality tracking, enhanced consumer confidence	Cost, integration into packaging systems	Singh et al., 2019 Zhang et al., 2022
QR Code-enabled	Integration of digital tracking and consumer	Traceability, consumer	Need for digital	Gupta et al., 2020

TECHNOLOGY	DESCRIPTION	KEY BENEFITS	CHALLENGES R
Packaging	engagement tools	awareness, supports recycling initiatives	infrastructure, consumer adaptation



9.12 ENVIRONMENTAL AND ECONOMIC IMPACT ANALYSIS

9.12.1 Life Cycle Assessment (LCA) of Dairy Packaging

Life cycle assessment (LCA) is a comprehensive methodology used to evaluate the environmental impact of a product from raw material extraction to end-of-life disposal. In the context of dairy packaging, LCA provides critical insights into resource consumption, greenhouse gas emissions, and the overall sustainability of different packaging materials ([Cappiello et al., 2021](#); [Santos et al., 2022](#); [Xie et al., 2011](#); [Desole et al., 2024](#); [Zhao et al., 2018](#)).

Recent studies have evaluated different packaging materials used in the dairy industry. [Desole et al. \(2024\)](#) compared conventional expanded polystyrene (EPS), polypropylene (PP), and polyethylene terephthalate (PET) trays with corrugated cardboard packaging coated with bioplastics. Their findings indicate that biopolymer-coated cardboard packaging significantly reduces carbon footprint and improves recyclability. However, they also highlight that bioplastics derived from corn and sugarcane require substantial agricultural input, leading to trade-offs in land and water use.

Furthermore, the study emphasized the end-of-life management challenges of different materials. While only 25% of EPS packaging is recycled, cardboard packaging achieves a 75% recycling rate, with an

additional 5% composted. However, PLA and PBSA films necessitate industrial composting conditions, which limit their large-scale adoption. This highlights the need for expanded industrial composting infrastructure to facilitate the transition to more sustainable dairy packaging solutions ([Desole et al., 2024](#)).

Another study by [Cappiello et al. \(2021\)](#) focused on the life cycle assessment of bio-based packaging for extended shelf-life (ESL) milk. Their analysis compared PLA-based bottles to PET, HDPE, multilayer carton, and glass bottles. The results demonstrated that bio-based solutions exhibit lower environmental impact in climate change, ozone depletion, and human toxicity categories. However, PLA production requires more agricultural land, raising concerns about indirect land-use change effects ([Cappiello et al., 2021](#)).

Dairy packaging contributes significantly to environmental burdens, with conventional petroleum-based plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) generating high levels of greenhouse gas emissions throughout their life cycles ([Xie et al., 2011](#)). Studies have demonstrated that bio-based alternatives, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), offer reduced carbon footprints compared to fossil-derived plastics, particularly when sourced from renewable feedstocks ([Cappiello et al., 2021](#); [IDF, 2022](#)). However, some bio-based plastics may have trade-offs, such as increased land and water use for agricultural raw materials ([Rosenboom et al., 2022](#)).

A life cycle assessment of milk packaging systems found that PET and HDPE bottles generate significant emissions during production, whereas PLA bottles have a lower environmental impact due to their compostability and biodegradability ([Cappiello et al., 2021](#); [Xie et al., 2011](#); [IDF, 2022](#)). Nevertheless, industrial composting facilities are required for the effective degradation of PLA, limiting its large-scale adoption ([Fogašová et al., 2022](#)).

A study by [Zhao et al. \(2018\)](#) analyzed the carbon footprint of a locally branded pure milk product using LCA. The research found that the production of raw milk contributed to approximately 75.27% of the total

carbon footprint, while packaging and transportation accounted for the remaining impact. The findings emphasize that, although packaging contributes a smaller fraction of the total emissions, switching to biodegradable or recyclable materials can significantly lower the overall environmental impact of dairy products. Additionally, the study underscores the importance of waste management infrastructure in determining the environmental feasibility of different packaging materials ([Zhao et al., 2018](#)).

A foundational study by [Ghenai \(2012\)](#) conducted a comparative LCA of various dairy packaging materials, including plastic, glass, aluminum, and carton containers. The study revealed that aluminum and glass packaging exhibit the highest embodied energy and CO₂ emissions due to their resource-intensive manufacturing processes. However, their ability to be reused significantly offsets their initial environmental cost, making them viable alternatives when incorporated into a closed-loop recycling system. The study further indicated that paper-based cartons coated with biodegradable polymers offer an optimal balance between environmental sustainability and functional performance, provided that industrial composting systems are available ([Ghenai, 2012](#)).

A study conducted by [Fry et al. \(2010\)](#) provided a comprehensive life cycle assessment (LCA) of different milk packaging systems used in the United Kingdom. The report evaluated a range of packaging formats, including HDPE bottles, PET bottles, flexible pouches, gable-top cartons, and cartons with screw caps, under various scenarios considering different levels of recycled content (0% to 50%) and weight reduction strategies. The findings indicated that reducing the weight of packaging materials by 10% led to the most significant environmental improvements across all categories. Additionally, recycling HDPE and PET bottles was found to be more effective in lowering greenhouse gas emissions compared to their virgin material counterparts.

[Fry et al.'s \(2010\)](#) study also emphasized that the production stage of packaging materials was the largest contributor to environmental impacts, highlighting the need for a transition toward lighter and more recyclable

packaging solutions in the dairy industry. Furthermore, the study showed that industrial composting, while beneficial for biodegradable materials like PLA, required specialized facilities, limiting its large-scale feasibility.

9.12.2 Regulatory Standards and Certification

To ensure the safety and sustainability of dairy packaging, multiple international regulatory frameworks govern the materials, migration limits, and end-of-life processing of packaging materials. Compliance with these standards is essential for market adoption and consumer acceptance.

Key Regulatory Frameworks

Several global entities have established regulations for food-contact materials, ensuring that packaging does not leach harmful substances into dairy products. Some of the most critical regulations include:

- European Union Regulation (EU) No. 10/2011—Establishes migration limits for plastic food-contact materials.
- US FDA 21** CFR**—Provides guidelines for food-safe packaging materials, including biodegradable plastics.
- ANVISA (Brazilian Health Regulatory Agency)—Regulates packaging materials for dairy products in Brazil.
- ISO 18604—Sets guidelines for material recovery, including recyclability and compostability.

These regulations focus on chemical safety, environmental impact, and waste management, ensuring that new packaging materials align with sustainability goals while maintaining food safety ([Ghenai, 2012](#); [Santos et al., 2022](#)).

Certification for Biodegradable and Compostable Packaging

In addition to regulatory frameworks, third-party certifications validate the sustainability of biopolymer-based packaging. Some of the key certifications include the following:

- ASTM D6400 (USA)—Defines industrial compostability standards for biodegradable plastics.
- EN 13432 (EU)—Specifies criteria for industrially compostable packaging materials.
- OK Compost (TÜV Austria)—Certifies packaging that fully degrades in industrial composting facilities.
- Cradle-to-Cradle Certification—Evaluates the sustainability of packaging based on material safety, recyclability, and renewable energy use.

Achieving these certifications is essential for market credibility and consumer trust, as they ensure that packaging materials adhere to sustainability and safety benchmarks ([Ghenai, 2012](#); [Santos et al., 2022](#)). In addition to biodegradability and compostability certifications, environmental sustainability certifications play a crucial role in ensuring the ecological responsibility of dairy packaging materials. These certifications validate the use of responsibly sourced raw materials. A key example is Forest Stewardship Council™ (FSC™) certification, which guarantees that paper-based packaging materials come from responsibly managed forests that meet rigorous environmental and social standards. Another significant certification is Bonsucro, which ensures that sugarcane-derived bioplastics follow sustainable agricultural practices, minimizing deforestation, optimizing water use, and reducing greenhouse gas emissions ([Tetra Pak, 2023](#)).

These certifications align with scientific findings on sustainable dairy packaging. A systematic review on sustainability indicators in the dairy industry highlighted that traceability and certification are fundamental in improving environmental performance and ensuring compliance with global sustainability goals ([Feil et al., 2020](#)). Additionally, research on the

effectiveness of environmental certification programs indicates that certified products generally have a lower carbon footprint, improved recyclability, and greater acceptance by consumers ([Blackman & Rivera, 2010](#)).

However, challenges remain in the widespread adoption of sustainability certifications. A meta-analysis on sustainability certification systems found that while certifications can enhance environmental transparency and consumer trust, they are sometimes criticized for greenwashing or for failing to enforce strict environmental standards ([Nygaard, 2023](#)). To mitigate this, certification bodies must ensure independent auditing and continuous improvements in sustainability criteria. In the dairy industry, large-scale adoption of sustainability certifications can drive the shift toward fully circular packaging systems, where materials are renewable, recyclable, and responsibly sourced. By integrating certified materials into dairy packaging, companies can reduce environmental impacts, meet regulatory requirements, and enhance their brand image as environmentally conscious companies, ensuring compliance with environmental and ethical standards.

9.12.3 Market Challenges and Industrial Adoption

Despite the growing interest in sustainable dairy packaging, several economic and logistical barriers still hinder its widespread adoption. Biopolymer production relies on agricultural raw materials such as corn, sugarcane, and whey protein, making it vulnerable to fluctuations in agricultural production and market prices ([Cappiello et al., 2021](#)). Compared to petroleum-based plastics, biopolymers have higher production costs due to the complexity of the extraction and manufacturing processes ([Xie et al., 2011](#); [Santos et al., 2022](#)). While large dairy companies can invest in biodegradable alternatives, small producers often face financial challenges in making this transition ([Ghenai, 2012](#)). Government policies such as subsidies, tax incentives, and corporate sustainability initiatives can help reduce this disparity and make environmentally friendly packaging

more affordable. Waste management infrastructure also plays a critical role in the success of biopolymer-based packaging. While compostable packaging can reduce the accumulation of plastic waste, its effectiveness depends on the availability of industrial composting facilities, which are still limited in many regions ([Santos et al., 2022](#)). In contrast, recycling programs for PET and HDPE are widely established, making them a more viable short-term solution for sustainable dairy packaging. To enable the use of biodegradable materials, investments in composting infrastructure and consumer education on the proper disposal of these materials are needed ([Cappiello et al., 2021](#)).

The demand for sustainable packaging is growing among consumers, but there are still knowledge gaps and misconceptions about the recyclability and compostability of different materials ([Ghenai, 2012](#)). Studies indicate that clear labels, environmental certifications, and sustainable branding significantly influence purchasing decisions and encourage the adoption of biopolymer-based packaging ([Cappiello et al., 2021](#)). Research by [Fry et al. \(2010\)](#) highlighted the importance of infrastructure in the effective management of dairy packaging waste. The study revealed that although recycling PET and HDPE bottles provided significant environmental benefits, the lack of access to recycling facilities in certain regions posed a significant challenge. Furthermore, countries with well-established recycling systems benefited more from lightweight and recyclable packaging than those that relied on landfills.

Another crucial aspect identified by [Fry et al. \(2010\)](#) was the need to increase consumer awareness of recyclable and compostable packaging. The study showed that standardized environmental labels and sustainability certifications play a key role in guiding purchasing decisions. According to market research, around 70% of consumers consider it important that their packaging is made from plant-based materials, driving the adoption of innovative solutions in the dairy sector ([Tetra Pak, 2023](#)). However, despite this growing interest, the level of consumer awareness of sustainability in packaging still varies considerably.

A systematic review on the adoption of sustainable packaging suggests that although consumers show a preference for environmentally friendly alternatives, the willingness to pay a higher price remains a significant barrier ([Popovic et al., 2019](#)). Studies also indicate that certification and labeling programs can improve market acceptance by clarifying the benefits and environmental impacts of sustainable packaging ([Boz et al., 2020](#)). Furthermore, consumer perception research shows that factors such as convenience, durability, and recyclability influence packaging choices. Consumers tend to prefer bioplastics that combine sustainability with functional characteristics similar to those of conventional plastics ([Schiano et al., 2020](#)).

Yet, misconceptions about recyclability and biodegradability continue to create confusion. For example, some consumers overestimate the sustainability of biodegradable plastics, assuming that they degrade in any environment, when in reality many require specific industrial composting conditions ([Otto et al., 2021](#)). To drive the widespread adoption of sustainable dairy packaging, it is essential to bridge this knowledge gap through awareness campaigns, corporate transparency, and standardized environmental labeling ([Popovic et al., 2019](#)). By integrating sustainability messages into product marketing and improving consumer education on proper packaging disposal, dairy producers can build trust and promote more responsible consumption habits.

The environmental and economic issues of dairy packaging require a holistic approach. Life cycle assessment (LCA) studies highlight the challenges and trade-offs between reducing the carbon footprint, water and energy consumption, and managing the end-of-life of packaging. While biopolymer-based packaging offers promising sustainable benefits, its success depends on regulatory compliance, market viability, and the development of adequate infrastructure. Future research should focus on improving biopolymer processing technologies, expanding composting facilities, and increasing consumer awareness to accelerate the transition to a fully sustainable dairy packaging industry.

9.13 CONCLUSION AND FUTURE PERSPECTIVES

9.13.1 Synthesis of Advances and Applications

The development and application of sustainable biomaterials for dairy packaging represent a significant step toward reducing the environmental impact of the dairy industry. Biopolymers, derived from natural sources such as polysaccharides, proteins, and biodegradable synthetic materials, offer promising alternatives to petroleum-based plastics. These materials provide essential functional properties, including mechanical strength, barrier performance, and biodegradability, making them suitable for dairy packaging applications. However, technical challenges remain, particularly concerning cost, large-scale production feasibility, and ensuring that new materials meet regulatory food safety requirements.

9.13.2 Emerging Technologies and Innovation

Recent advances in nanotechnology, active and intelligent packaging, and the development of next-generation biopolymers have demonstrated great potential for the dairy industry. Nanocomposites can enhance the mechanical and barrier properties of biopolymer films, increasing their viability for dairy applications. Active packaging systems incorporating antimicrobial agents and antioxidants extend the shelf life of dairy products, while intelligent packaging solutions with freshness indicators improve food safety and consumer awareness. Furthermore, the integration of agro-industrial residues into biopolymer production aligns with circular economy principles, optimizing costs and minimizing environmental impacts. Research into novel bio-based coatings, enzymatic modifications, and hybrid material compositions may further improve packaging performance and sustainability.

9.13.3 Regulation and Adoption in the Sector

The adoption of sustainable dairy packaging requires supportive regulatory frameworks and industry collaboration. Government incentives, tax benefits, and funding for research and development (R&D) can accelerate the commercialization of biodegradable and compostable packaging solutions. Universities and research institutions play a critical role in advancing technological innovations and ensuring the safety and efficiency of new materials. However, current regulatory gaps and regional inconsistencies pose challenges for global standardization. The development of harmonized policies that facilitate the market entry of sustainable packaging solutions, while maintaining stringent food safety standards, is essential. Additionally, investment in consumer education is necessary to enhance acceptance and encourage proper disposal and recycling practices.

9.13.4 Final Message

Sustainable packaging is a fundamental component of the future of the dairy industry. As global environmental concerns intensify, the transition to eco-friendly materials will play a key role in reducing plastic pollution, carbon footprint, and resource depletion. Advancing research in biomaterials, improving processing technologies, and expanding recycling and composting infrastructures will be critical to the successful implementation of sustainable solutions. Collaboration among industry leaders, policymakers, and researchers is necessary to overcome current limitations and drive the development of accessible and scalable packaging alternatives. Ultimately, investing in sustainable dairy packaging is not only an environmental responsibility but also an economic opportunity to align the industry with circular economy principles and consumer demand for greener products.

9.14 CONCLUSION

The transition to sustainable biomaterials in the dairy packaging industry is essential to reduce environmental impacts by replacing conventional plastics with biodegradable alternatives. Despite technological advances, challenges such as high costs, scalability, and regulation still limit their large-scale adoption. The use of nanotechnology, active, and smart packaging has improved the functionality of these materials, extending the shelf life of products and ensuring greater food safety. However, government incentives, investment in research, and regulatory harmonization are necessary to make their implementation viable. The future of sustainable packaging depends on collaboration between industry, academia, and policymakers, driving the circular economy and meeting the growing demand for environmentally friendly solutions.

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Sustainable Biomaterials for Fruits and Vegetables 10

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10.1 INTRODUCTION

Fruits and vegetables are essential components of a healthy diet. The nutritional value of these foods lies in their content of micronutrients, fiber, and bioactive phytochemicals ([Botondi et al., 2021](#); [Pacheco et al., 2024](#)). Fruit and vegetable processing operations involve processes and technologies, such as peeling, cutting, washing, treatments with sanitizing agents, and drying. ([Dar et al., 2022](#)). These processing operations alter the physical integrity of these products, making them more susceptible to deterioration than the original raw materials ([Banerjee et al., 2016](#); [Dar et al., 2022](#)). In addition, the industrial process accelerates the degradation of minimally processed agricultural products and leads to biochemical changes, such as increased respiration rate, which accelerates oxidation processes, degradation of cell membranes and enzymatic darkening, and loss of tissue texture ([De Corato, 2020](#)).

Fresh fruits, whether whole or cut, are highly perishable and require appropriate preservation techniques to maintain their quality and extend their shelf life ([Giannakourou & Tsironi, 2021](#)). Whole fruits, while naturally protected by their outer skin, are still susceptible to moisture loss, microbial contamination, and degradation due to environmental factors ([Zhao et al., 2022](#); [Alegbeleye et al., 2022](#)). Proper handling, temperature control, and packaging are crucial to preserving their freshness. Fresh-cut fruits, on the other hand, are even more vulnerable due to exposure to cut surfaces, increasing susceptibility to enzymatic browning, microbial growth, and moisture loss ([Chen et al., 2024](#)). To slow down these deterioration processes, techniques such as refrigeration, controlled atmosphere storage, and the application of natural antioxidants like ascorbic acid are widely used ([Giannakourou & Tsironi, 2021](#)). Additionally, antimicrobial agents and edible coatings can enhance the preservation of both whole and fresh-cut fruits by reducing oxidation and microbial contamination ([Chen et al., 2024](#)).

Similarly, vegetables, whether whole or minimally processed, require strict handling and storage conditions to maintain their quality ([Finger et al., 2023](#)). Whole vegetables benefit from proper post-harvest practices, such as maintaining optimal humidity and temperature levels to reduce dehydration and microbial spoilage ([Janghu et al., 2024](#)). Minimally processed vegetables, such as pre-washed and chopped varieties, demand additional preservation measures to extend shelf life ([Benkeblia, 2024](#)). The use of sanitizing treatments, modified atmosphere packaging, and cold storage plays a vital role in slowing down degradation processes while ensuring food safety and nutritional retention.

In this context, the preservation of the sensory, nutritional, and microbiological qualities of fresh and minimally processed products represents a great challenge for the food industry ([Khalil et al., 2023](#)). Techniques such as refrigeration, use of preservatives, gentle heat treatments, microwave processing, ionizing radiation, high-pressure technology, high-intensity pulsed electric field, ozonation, and barrier technology, among others, have been shown to be effective alternatives to

maintain the microbiological and sensory quality of these products ([Khalil et al., 2023](#)). In addition to the processing conditions, choosing the appropriate packaging is crucial for maintaining the integrity of processed fruits and vegetables ([Giannakourou & Tsironi, 2021](#)). Around 40–50% of fruits and vegetables are wasted worldwide, either during the early stages of the food supply chain (production, post-harvest, and processing phases) or in food waste arising from markets, restaurants, and consumers ([Giannakourou & Tsironi, 2021](#)).

The packaging of food products has the primary function of protecting them against hazards, which are biological, physical, and chemical ([Flórez et al., 2022](#)). Materials such as polypropylene, polyethylene, polyesters, and polyamides are widely used due to their good physical and mechanical properties, as well as being affordable and efficient. However, the non-biodegradability of these polymers is one of their biggest drawbacks ([Dutta & Sit, 2024](#)). This has generated growing public awareness and demand for sustainable packaging materials, especially in the food industry. For this reason, there is a growing emphasis on the use of biopolymer-based food packaging, which offers a safer and more sustainable alternative ([Basumatary et al., 2022](#)).

Biopolymer-based packaging materials possess distinct characteristics such as biodegradability, renewability, and wide availability ([Basumatary et al., 2022](#)). They are widely used in the food industry, especially in the production of edible films, emulsions, and packaging materials. Common examples include carbohydrates, proteins, starch, cellulose, gelatin, chitosan, and others ([Dutta & Sit, 2024](#)). These packaging films loaded with functional ingredients protect food against physical, chemical, and biological hazards ([Liu et al., 2021](#)). Furthermore, the incorporation of various antimicrobial and antioxidant agents in packaging films offers potent antimicrobial and antioxidant activities ([Abdullah et al., 2022](#)).

Thus, this chapter seeks to investigate the current state of research that addresses using biomaterials to create biodegradable packaging. The study includes a more recent compilation on producing edible films and coatings using only biological components from a sustainability perspective, with an

approach favoring the circular economy. Their main characteristics and functionalities will be discussed, as well as their applications in fruits and vegetables. In addition, innovative technological advances, such as nanotechnology and edible films, will be addressed. This research can contribute to the food sector, which seeks to reduce dependence on non-renewable resources and reduce plastic waste significantly, adding value to the entire food supply chain.

10.2 BASIC PRINCIPLES OF FRUIT AND VEGETABLE SHELF-LIFE EXTENSION METHODS

Conventional methods of fruit and vegetable preservation mainly include physical preservation, chemical preservation, and biological preservation ([Gomes et al., 2023](#); [Chen et al., 2024](#)). Although each preservation method has a different emphasis, they all regulate three main factors that play a key role in preserving quality ([Figure 10.1](#)).

Conventional methods have some shortcomings in extending the shelf life of fruits and vegetables; therefore, it is necessary to develop new fruit and vegetable preservation technologies to meet the growing emphasis of consumers on food safety and the demand for food freshness ([Table 10.1](#)).

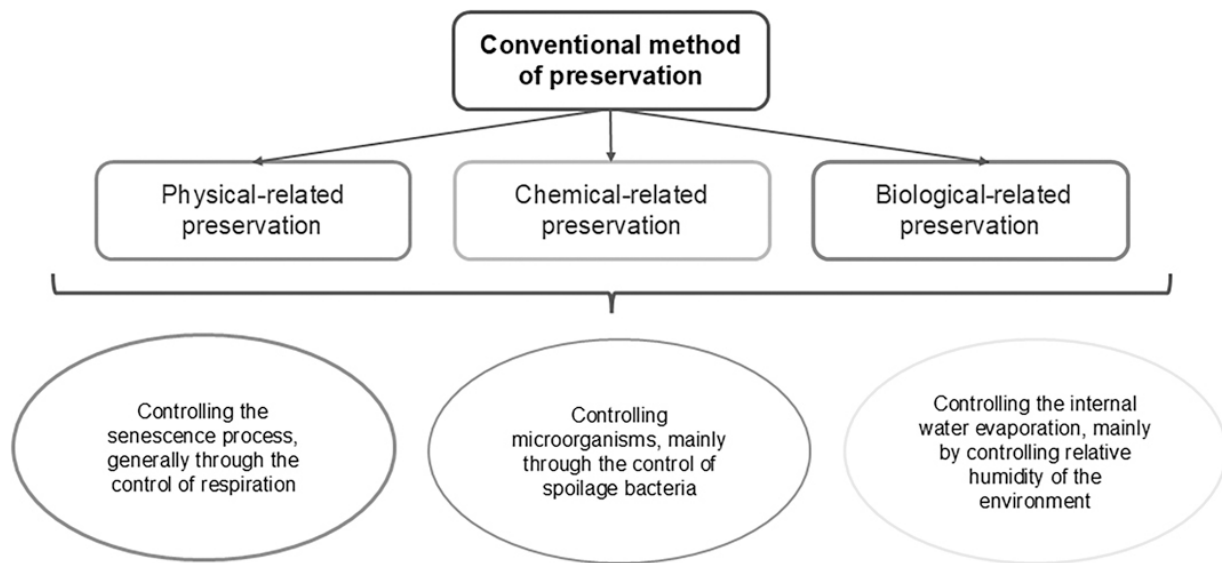


FIGURE 10.1 Conventional methods of fruit and vegetable preservation and their main factors in preserving quality. [↗](#)

TABLE 10.1 Disadvantages of Common Shelf-Life Extension Techniques of Fruits and Vegetables [↗](#)

<i>SHELF LIFE EXTENSION TECHNIQUES</i>	<i>DISADVANTAGES</i>
Cold storage	Self-cost and potential risks of cold or frostbite injuries
Heat treatment	Loss of nutrients such as vitamins and minerals
Modified atmosphere package	High cost and safety risk, in addition to being difficult to operate
High hydrostatic pressure	High investment
Irradiation	High cost and difficult-to-control radiation conditions
Edible coating	Short shelf life, low moisture resistance, and the difficult-to-control thickness of the material

<i>SHELF LIFE EXTENSION TECHNIQUES</i>	<i>DISADVANTAGES</i>
Chemical-based preservation technology	Formation of residue and low safety

Fonte: [Chettri et al. \(2023\)](#); [Meneses-Espinosa et al. \(2024\)](#).

Cold storage, while one of the most common and effective options, involves a high cost of refrigeration infrastructure and can generate risks of cold injuries, such as frostbite, if control conditions are not well managed. This factor increases operating costs and can affect product quality ([Gomes et al., 2023](#)). Heat treatment (such as sterilization, blanching, and pasteurization) is efficient in destroying microorganisms and preserving food, but it can also cause the loss of vitamins, minerals, and other essential nutrients. This results in a degradation of the nutritional and sensory quality of fruits and vegetables, altering their texture and flavor, which can be undesirable, especially in fresh produce. Modified atmosphere technology, which involves controlling the composition of the air around the food (such as oxygen, carbon dioxide, and nitrogen), can improve the durability of products, but it has operational difficulties and high production costs. In addition, safety risk is a concern, as the handling of specific gases requires strict control, which may limit the adoption of this technique on a large scale. High hydrostatic pressure (HPP) is another effective technique that preserves the nutritional quality of food without the use of heat. However, it requires a high initial investment in specialized equipment, making it an unaffordable option, especially for small producers. Irradiation is also an alternative for preservation, but it faces challenges due to its high cost and difficulty in controlling radiation conditions. In addition, public acceptance of the technology can be an obstacle, as many consumers still have fears about the effects of irradiation on food ([Gomes et al., 2023](#); [You et al., 2023](#); [Chen et al., 2024](#)).

Edible films and coatings have gained prominence as a sustainable alternative but face problems related to their unsatisfactory shelf life and low resistance to moisture ([Gupta et al., 2024](#)). The ease with which coatings absorb moisture can compromise their effectiveness, allowing food to deteriorate more quickly ([Tyagi et al., 2021](#)). In addition, controlling the concentration and thickness of the coating is challenging, which can affect the uniformity and quality of the application ([Gupta et al., 2024](#)). The use of chemical substances can affect consumer perceptions of product safety, as well as raise concerns regarding the long-term health impact ([Olawore et al., 2024](#)).

Thus, while each technique has benefits, all have limitations that need to be carefully evaluated. The high cost, nutrient loss, operational complexity, and risks associated with some of these technologies require food industries to seek balanced and innovative solutions. The development of new technologies or the combination of these approaches can be the key to ensuring effective preservation, which meets consumer expectations and the environmental and economic challenges faced by the sector.

10.3 SUSTAINABLE BIOMATERIALS

Biomaterials are the best choice for ensuring the safety and quality of food items throughout the supply chain due to their wide range of capabilities ([Khan et al., 2023](#)). In order for biomaterials to become suitable for application in packaging, a number of properties are desirable, such as mechanical strength, a barrier to O₂, CO₂, and UV, resistance to temperature and humidity, biodegradability, recyclability, shelf life, solubility in water or lipids, pH dependence, physicochemical characteristics, and non-toxicity ([Tomasevic et al., 2017](#)). These characteristics depend on the type of biomaterial, as well as its derivatization and processing technologies. [Figure 10.2](#) illustrates the advantages of using biomaterials for food packaging.

To pave the way for a successful circular economy, researchers have developed a plethora of biomaterial-based strategies for food packaging. Different biomaterials are used in fruit and vegetable packaging to meet specific needs, and each has its benefits.

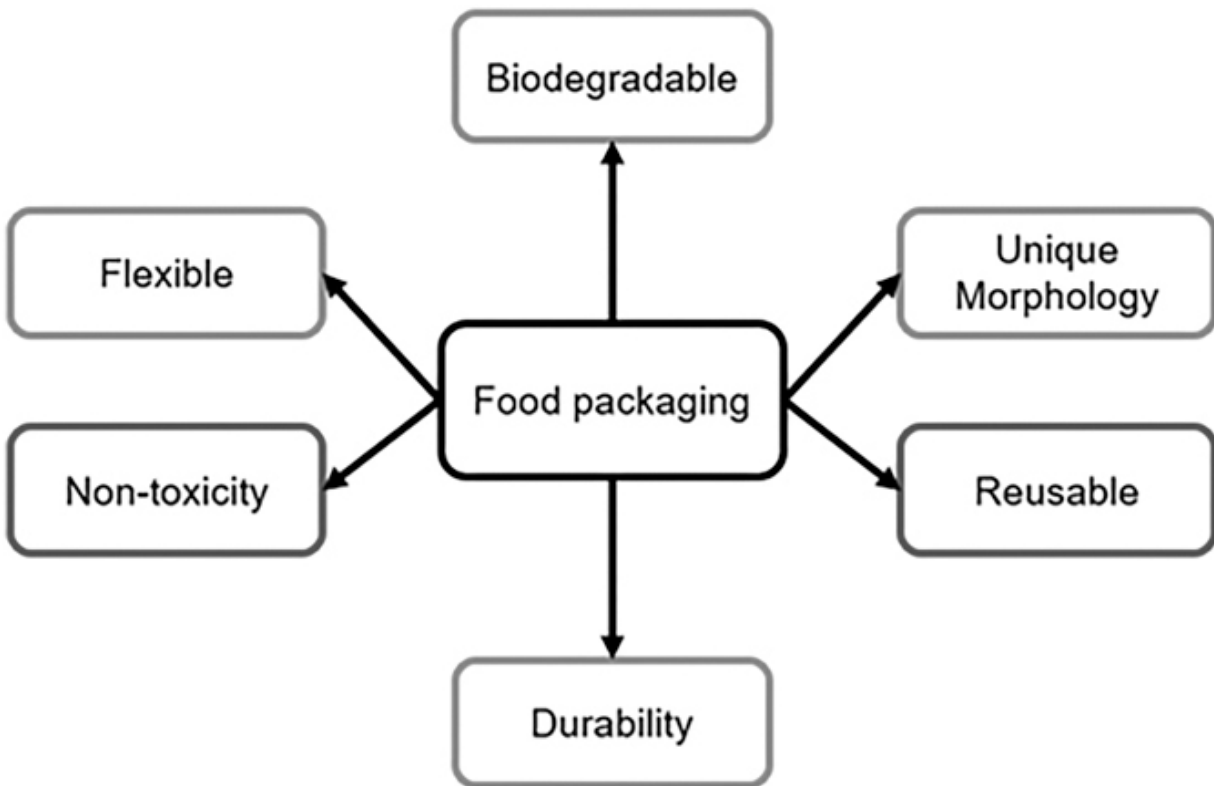


FIGURE 10.2 Advantages of biomaterials for food packaging. [↗](#)

10.3.1 Classification of Sustainable Biomaterials

Biopolymers can be classified based on their production methods and can be produced by living organisms or chemically synthesized from biological sources. They fall into three main categories: natural polymers, biosynthesized polymers, and microbial-based polymers ([Figure 10.3](#)) ([Dutta & Sit, 2024](#)).

Natural polymers are extracted directly from biomass and include polysaccharides, proteins, fats, etc. Biosynthesized polymers are produced by microorganisms and plants or synthesized from predominantly biosynthesized monomers, such as polyhydroxyalkanoates (PHAs) and

polylactic acid (PLA). Finally, microbial-based polymers, such as PHA and polyhydroxybutyrate (PHB), are synthesized by microorganisms from renewable sources and stand out for their biodegradable properties and their potential for sustainable applications ([Dutta & Sit, 2024](#)). [Table 10.2](#) summarizes the common biomaterials used in food packaging and their associated characteristics.

Biodegradable packaging materials derived from biomaterials, including proteins, polysaccharides, bio-based synthetic polymers, and microbial biopolymers, have gained significant attention for their potential to replace conventional plastics, offering a sustainable alternative to fossil fuel-based packaging ([Singh et al., 2021](#); [Akhila & Badwaik, 2022](#)). These materials, sourced from renewable resources, can be processed into biodegradable and environmentally friendly packaging solutions for fruits and vegetables. Among the most studied biopolymers, proteins and polysaccharides play a crucial role due to their natural abundance and versatility.

Proteins, which are key structural components in plant and animal cells, exhibit various functional properties such as water and oil absorption, foaming, gelling, and emulsification ([Duro-Castano et al., 2014](#)). Despite their low environmental impact and biodegradability, protein-based packaging faces challenges such as low mechanical strength and high gas permeability under humid conditions, limiting their wide-scale application ([Hadidi et al., 2022](#)). In contrast, polysaccharides—long chains of monosaccharides linked by glycosidic bonds—are extensively researched for biodegradable packaging due to their ease of processing and abundance. Polysaccharide-based films, derived from sources such as fruits and vegetables, can act as natural barriers to oxygen and moisture, extending shelf life while being biodegradable ([Asgher et al., 2020](#); [Gupta et al., 2024](#)). Moreover, these films can be enriched with antioxidants or antimicrobial agents to enhance food preservation, although challenges such as economic feasibility and consistent material quality need to be addressed ([Asgher et al., 2020](#)).

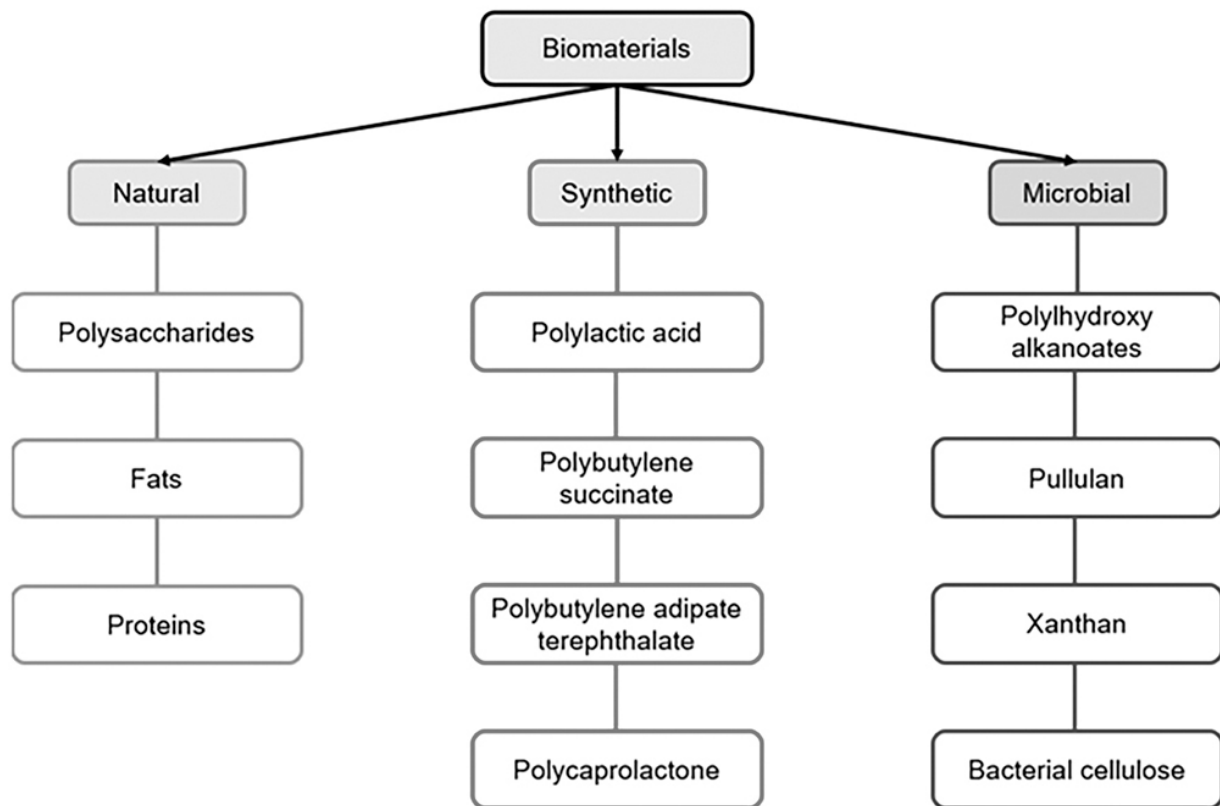


FIGURE 10.3 Classification of some biodegradable biomaterials. [↗](#)

TABLE 10.2 Common Biomaterials Used in Food Packaging and Their Associated Characteristics [↗](#)

<i>CLASSIFICATION</i>	<i>BIOMATERIALS</i>	<i>PACKAGING APPLICATION</i>	<i>REFERENCES</i>
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<i>CLASSIFICATION</i>	<i>BIOMATERIALS</i>	<i>PACKAGING APPLICATION</i>	<i>REFERENCES</i>
Polysaccharides	Cellulose	Edible coating	Abral et al. (2020)
	Chitosan	Antimicrobial film	Cazón and Vázquez (2020)
	Starch	Films with antimicrobial or antioxidant agents	Żołek-Tryznowska et al. (2024)
	Bacterial cellulose	Edible films & coatings	Xu et al. (2021)
	Pectin	Smart packaging with antimicrobial and antioxidant agents	Roy et al. (2023)

<i>CLASSIFICATION</i>	<i>BIOMATERIALS</i>	<i>PACKAGING APPLICATION</i>	<i>REFERENCES</i>
Proteins	Collagen	Multifunctional films with active and intelligent functions	Tang et al. (2022)
	Gelatin	Edible films & coatings	Lu et al. (2022)
	Whey protein	Active films with antimicrobial agents	Al-Hilifi et al. (2023)
	Keratin	Composite films with active characteristics	Li et al. (2021)
	Zein	Edible coating, active films with antimicrobial properties	Ansarifar and Moradinezhad (2021)
Synthetic	Polycaprolactone (PCL)	Viscoelasticity and ease of modeling	Shen et al. (2024)
	Polylactic acid (PLA)	Thermoplasticity, non-toxicity, and good mechanical properties	Naser et al. (2021)

<i>CLASSIFICATION</i>	<i>BIOMATERIALS</i>	<i>PACKAGING APPLICATION</i>	<i>REFERENCES</i>
Microbial	Polyhydroxybutyrate (PHB)	Biocompatibility, biodegradability, non-toxicity, thermoplasticity, and water barrier properties	Marasinghe et al. (2024)
	Polyhydroxyalkanoates (PHA)	Biodegradable, biocompatible, and independent of fossil resources	Kovalcik et al (2019)
	Bacterial cellulose (BC)	Chemically pure, has high crystallinity, purity, tensile strength, and a large surface area	Xu et al. (2021)

Beyond proteins and polysaccharides, bio-based synthetic polymers and microbial biopolymers are becoming increasingly relevant in fruit and vegetable packaging. Polymers like polylactic acid (PLA) and poly(ϵ -caprolactone) (PCL), derived from renewable plant sources such as corn, cassava, and agro-industrial residues, offer biodegradable alternatives to conventional plastics ([Archer et al., 2021](#)). PLA, in particular, exhibits mechanical properties comparable to conventional plastics and is widely used in food films and biodegradable packaging. Similarly, microbial biopolymers, such as polyhydroxyalkanoates (PHAs), polyhydroxybutyrate (PHB), and bacterial cellulose (BC), produced by microorganisms using plant-based substrates, are gaining attention for their excellent

biodegradability and mechanical properties ([Domżał-Kędzia et al., 2023](#); [Dutta & Sit, 2024](#)). These biopolymers, derived from fruits and agricultural residues like banana peels and sugarcane bagasse, offer cost-effective solutions for large-scale production of biodegradable packaging, reducing reliance on traditional plastics and minimizing environmental impact.

◀ In the context of food preservation, polysaccharide-based films have been shown to be highly effective in extending the shelf life of fruits and vegetables, maintaining their nutritional, sensory, and microbiological properties ([Galus & Lenart, 2019](#)). These films provide a natural barrier to moisture, oxygen, and gases, helping preserve the freshness of produce. Additionally, protein biomass materials are ideal candidates for biodegradable packaging due to their biodegradability, low cost, and biocompatibility. When used as coatings, they help reduce weight loss, delay senescence, and can even replace plastic packaging, further mitigating waste disposal problems ([Chen et al., 2024](#)).

Overall, a wide range of biomaterials, including proteins, polysaccharides, synthetic biopolymers like PLA, and microbial biopolymers like PHAs and PHB, offer sustainable solutions for biodegradable packaging in the food industry. These materials address the environmental concerns of conventional plastic packaging while also meeting the preservation needs of fruits and vegetables. However, challenges related to economic feasibility, consistent material quality, and large-scale implementation remain, necessitating further research and technological advancements ([Dutta & Sit, 2024](#)).

10.3.2 Properties of Sustainable Biomaterials

10.3.2.1 Mechanical and Barrier Properties of Biomaterials

Biodegradable films have been increasingly explored for fruit and vegetable packaging, aiming to replace conventional plastic films commonly used in supermarkets. These plastic films are highly transparent, help retain moisture, and preserve the aroma of packaged fruits and vegetables,

ensuring their freshness ([Abdul Khalil et al., 2018](#)). However, biomaterial-based films often have limitations in their barrier properties, which can restrict their effectiveness in food preservation ([Calva-Estrada et al., 2019](#)). The large-scale adoption of bio-based films for fruits and vegetables depends on improving their mechanical strength and permeability to compete with commercial packaging solutions ([Mazhandu et al., 2020](#)). Effective fresh produce packaging requires controlled oxygen (O₂) and carbon dioxide (CO₂) permeability to prevent oxidation, browning, and microbial growth, while water vapor permeability (WVPC) ensures optimal moisture levels ([Chaudhary et al., 2020](#); [Khalil et al., 2023](#); [Mohamed et al., 2020](#)).

Biodegradable films with plant residues generally have lower tensile strength than commercial polymers, and their higher water permeability may require modifications for improved resistance ([Zhang & Sablani, 2021](#); [Rodsamran & Sothornvit, 2019](#)). Additives like cranberry pomace, apple puree, and mango leaf extract enhance oxygen and moisture barriers, mechanical strength, and UV protection, making biodegradable films more suitable for fruit and vegetable packaging ([Park & Zhao, 2006](#); [Rambabu et al., 2019](#)).

Overall, biodegradable films tailored for fruits and vegetables require careful optimization of barrier and mechanical properties to ensure effective food preservation. Advances in material formulation, including the incorporation of plant-derived reinforcements and functional additives, can improve the performance of bio-based films, making them a viable alternative to traditional plastic packaging.

10.3.2.2 Antimicrobial and Antioxidant Action of Biomaterials

Extending the shelf life of fresh fruits and vegetables faces two main microbiological challenges: spoilage caused by physiological processes and microbial activity and the presence of human pathogens that can multiply during the production cycle ([Wang & Teplitski, 2023](#)). Biomaterials have hydrophobic properties that confer a potent antimicrobial action, acting by

two main mechanisms: direct inhibition of pathogen growth through specific biochemical reactions and indirect protection by strengthening the resistance of food against pathogens through the induction of defensive enzymes ([Figure 10.4](#)) ([Roy et al., 2022](#)). However, challenges such as a lack of technical knowledge, possible allergic reactions, food safety issues, sensory impacts, and high costs make it difficult to adopt and commercialize widely.

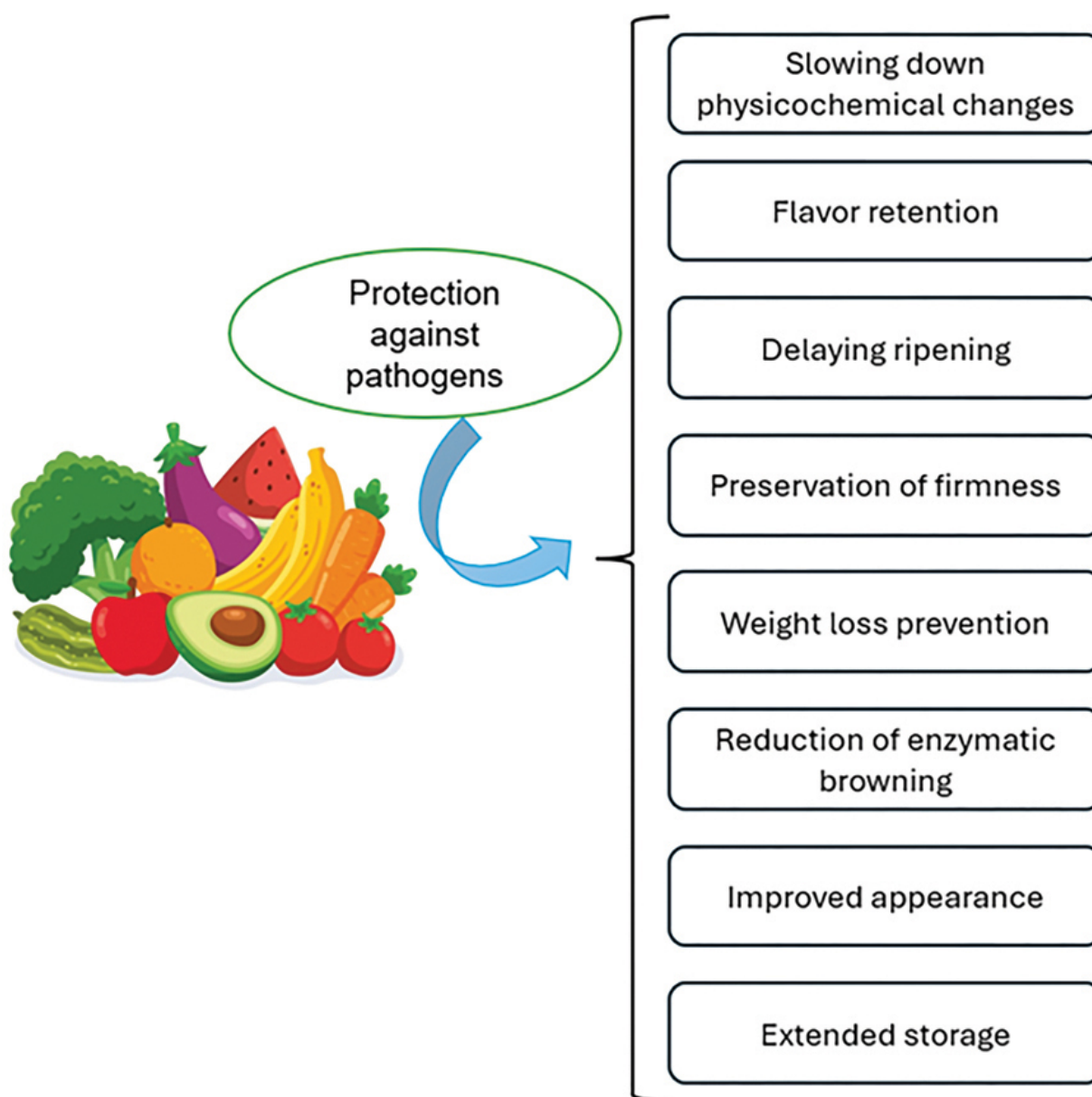


FIGURE 10.4 Impact of biomaterial coating on fruits and vegetables. [14](#)

In a study conducted by [Kubheka et al. \(2020\)](#), the potential of a formulation composed of Moringa oleifera leaf extract, gum arabic (GA), and carboxymethyl cellulose (CMC) as an organic biofungicide was evaluated in the proportions GA 10%, GA 15%, GA 10% + M, GA 15% + M, and CMC 1% + M, and the uncoated fruit served as a control. This combination demonstrated efficacy in the storage of avocados, indicating a promising solution to extend the shelf life of highly perishable fruits such as acerola, papaya, and mango. The coatings GA 15% + M and CMC 1% + M were the most effective in preserving firmness (62.37 N), reducing mass loss (3.66%), and maintaining fruit color during storage. Furthermore, treatments with moringa extract suppressed the mycelial growth of *C. gloeosporioides* by up to 33%.

In the studies by [Moghadam et al. \(2020\)](#) and [Rodsamran and Sothornvit \(2019\)](#), the addition of pomegranate peel powder and lemon peel extract has the potential to increase the phenolic content and antioxidant activity of the films, in addition to delaying the oxidation of soybean oil. In the study by [Moghadam et al. \(2020\)](#), mung bean protein films enriched with different concentrations (0, 2.5, 12.5, and 25% w/w) of pomegranate peel increased radical scavenging activity (ABTS and DPPH, respectively) by up to 240.5% and 1204.4%. In the study by [Rodsamran and Sothornvit \(2019\)](#), the increase was 2704.2% and 317.9% for ABTS and DPPH, respectively. Films with black plum peel extract, chitosan, and titanium oxide nanoparticles eliminated free radicals by up to 90% and reduced ethylene with pH-sensitive colors due to anthocyanins ([Zhang et al., 2019](#)). These results demonstrate that in addition to extending the shelf life of products, these biomaterials can promote an increase in antioxidant properties that are important for health.

10.3.2.3 Choosing Biomaterials for Fruit and Vegetable Packaging

In general, biopolymers are more sensitive to environmental conditions, such as temperature and chemicals, which require greater precision during

manufacturing and, consequently, can result in higher costs. On the other hand, it is expected that the adoption of practices in favor of the circular economy will trigger the development of biomaterial-based packaging ([Das et al., 2023](#); [Dey et al., 2024](#)). The key considerations for choosing the right material and processing approach for food packaging are shown in [Figure 10.5](#).

The choice of biomaterials for food packaging is an increasingly relevant issue, given the growing concern for the environment and the need to reduce the use of conventional plastics ([Roy et al., 2022](#)). These materials must meet a series of criteria to ensure that they are sustainable, safe, and efficient in preserving food. One of the most important aspects is sustainability, as biomaterials must be obtained from renewable sources, such as natural polymers extracted from plants, algae, or agro-industrial waste ([Rout et al., 2022](#)). In addition, their production must minimize environmental impacts, reducing carbon emissions and the consumption of natural resources. Implementing a model based on the circular economy is also essential to maximize the environmental benefits of biomaterials. This means that packaging must be designed to be reused, recycled, or degraded naturally without leaving harmful residues in the environment ([Chakrapani et al., 2022](#)). This concept reduces dependence on virgin raw materials and contributes to reducing the volume of plastic waste in ecosystems.

In addition to sustainability, the safety of biomaterials must be a priority since these materials come into direct contact with food ([Roy et al., 2022](#)). It is essential that they do not release toxic substances or contaminants that could compromise the health of consumers. To this end, biomaterials must undergo rigorous toxicity tests and comply with international health regulations ([Chakrapani et al., 2022](#)).

Another essential factor in choosing biomaterials is mechanical resistance and barrier properties. Packaging must be durable and capable of protecting food against moisture, oxygen, and microorganisms that could accelerate its degradation ([Nilsen-Nygaard et al., 2021](#)). Some biodegradable packaging still faces challenges in this area, as it tends to be less resistant than conventional plastics. However, technological advances

have allowed the development of reinforced biomaterials that offer effective protection without compromising their biodegradability ([Dey et al., 2024](#)). Barrier properties are essential to maintaining the quality and extending the shelf life of food. Moisture barriers prevent the penetration of water and vapor, which can stimulate microbial growth and alter the texture and flavor of food ([Trinh et al., 2023](#)). Oxygen barriers limit the entry of this gas, reducing oxidation, deterioration, and loss of nutritional value and flavor. These barriers are formed by materials that create a tortuous path for gas and moisture molecules, thus reducing permeability.

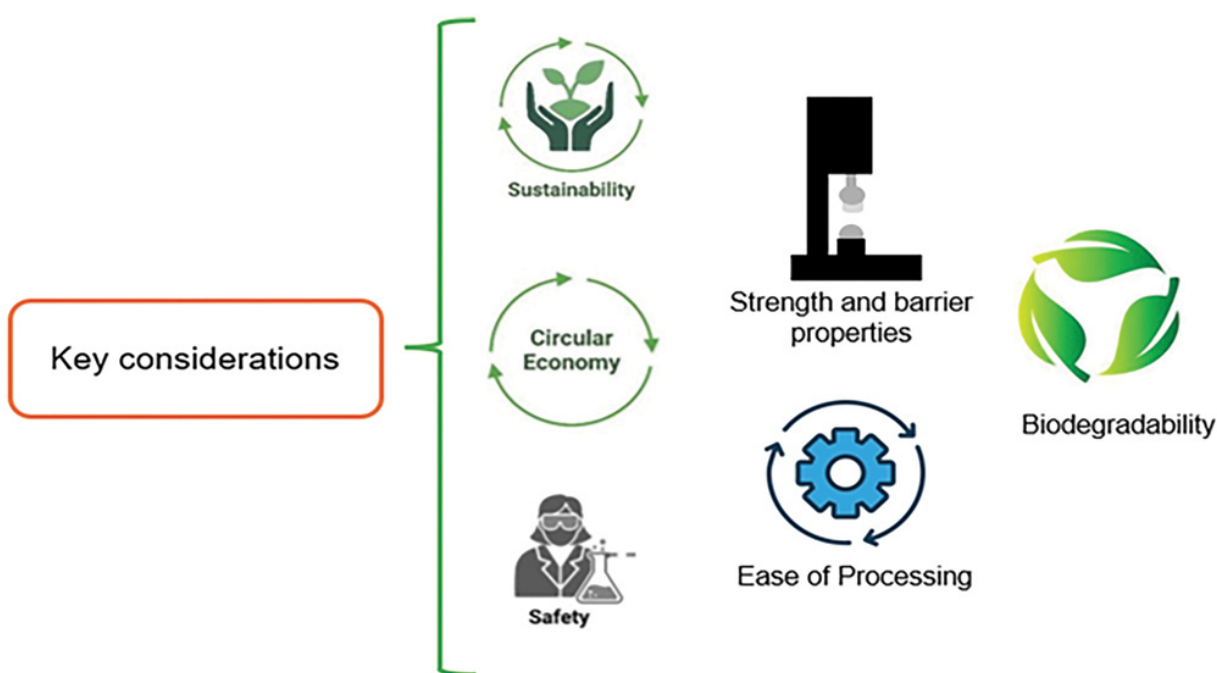


FIGURE 10.5 Key considerations for choosing biomaterials for food packaging. [↗](#)

Biodegradability is, in fact, one of the greatest advantages of biomaterials over traditional plastic packaging ([Panou & Karabagias, 2024](#)). A biodegradable material can decompose naturally through the action of microorganisms, transforming into organic compounds that are harmless to the environment ([Qin et al., 2021](#)). However, it is important to consider that not all biomaterials have the same degradation rate. Some require specific conditions, such as controlled temperature and humidity, to decompose completely. Finally, the ease of processing of biomaterials must be taken

into account to enable their large-scale adoption ([Panou & Karabagias, 2024](#)). They need to be compatible with manufacturing technologies already used in the industry, such as extrusion, injection molding, and thin film printing. The development of biomaterials that can be processed efficiently, without the need for major industrial adaptations, facilitates their implementation and reduces production costs ([Kumar & Agrawal, 2023](#)).

10.4 APPLICATION OF BIOMATERIAL-BASED PACKAGING IN FRUITS AND VEGETABLES

10.4.1 Biomaterials from Different Sources for Packaging in Fruits and Vegetables

As discussed earlier, the use of biomaterial packaging materials that provide effective barriers to water vapor and oxygen becomes an essential strategy to preserve food quality. [Table 10.3](#) presents different studies involving the application of biomaterial-based packaging in fruits and vegetables.

TABLE 10.3 Studies Involving Biomaterial-Based Packaging in Post-Harvest Fruits and Vegetables [↗](#)

<i>TYPE OF FILM</i>	<i>FOOD</i>	<i>EFFECTIVENESS</i>	<i>REFERENCE</i>
Chitosan/cellulose acetate phthalate/ZnO	Black grapes	The packaging can prevent the invasion of bacteria and fungi that spoil food in fruits	Indumathi et al. (2019)
Carrageenan/glucomannan	Strawberry	Reduced weight loss and acidity	Duan et al. (2021)

<i>TYPE OF FILM</i>	<i>FOOD</i>	<i>EFFECTIVENESS REFERENCE</i>
		during storage
Poly(vinyl alcohol)/chitosan incorporated with D-limonene	Sleeves	It has an extended shelf life with a spoilage rate of less than 20% after 10 days of storage Lan et al. (2020)
Clove/chitosan oil incorporated into gelatin nanofibers	Cucumber	It eliminated bacterial biofilms and maintained the sensory quality of cucumber samples Cui et al. (2018)
Xanthan gum enriched with cinnamic acid	Fresh pears	It maintained color, inhibited PPO and POX activity, and delayed the incidence of browning Sharma and Rao (2015)
Cellulose nanocrystals (CNCs), egg whites, and egg yolks	Bananas, avocados, papayas, and strawberries	Lower water vapor and oxygen permeability (OP), preserving the freshness of the fruit and reducing weight loss during storage Jung et al. (2020)
Starch	Sleeves	The concentration of ethylene Ounkaew et al. (2021)

<i>TYPE OF FILM</i>	<i>FOOD</i>	<i>EFFECTIVENESS</i>	<i>REFERENCE</i>
		decreased	
Soy protein	Tomatoes	It delayed ripening and reduced softening	Ortiz et al. (2013)
Zein	Cherry tomatoes	Decreased ethylene concentration	Böhmer-Maas et al. (2020)

The research of [Jung et al. \(2020\)](#) exemplifies an effective strategy to solve both oxygen and water permeability problems. They studied packaging made from cellulose nanocrystals combined with egg whites and egg yolks, which demonstrated superior performance in reducing permeability to water vapor and oxygen. This helped preserve the freshness of fruits, such as bananas, avocados, papayas, and strawberries, as well as reduce weight loss during storage. The use of natural biopolymers, such as cellulose and egg proteins, combines environmental and functional advantages, offering a more sustainable and effective solution for food preservation.

Ethylene is a plant hormone that plays a crucial role in the ripening and spoilage of many post-harvest products, such as fruits and vegetables. Regulating the concentration of ethylene in packaging is, therefore, a key aspect of extending the shelf life of post-harvest products ([Gaikwad et al., 2020](#)). Generally, the regulation of ethylene is mainly as follows: (1) oxidation, (2) ethylene blockage, and (3) adsorption. The study by [Böhmer-Maas et al. \(2020\)](#) offers an innovative solution for the control of ethylene in food packaging, using photocatalytic nanofibers composed of zein (a vegetable protein) and TiO₂ (titanium dioxide). This material is able to absorb ethylene efficiently, acting as an active packaging. The results of the study indicated that the cherry tomato packages containing sachets of zein-TiO₂ nanofibers showed a significant reduction in the concentration of ethylene within the internal environment. While the results presented in

[Table 10.5](#) are promising, additional research is needed to optimize these technologies, explore new sources of biopolymers, and assess the environmental and economic impact of their large-scale adoption.

In another study, [Meng et al. \(2024\)](#) developed biodegradable polysaccharide-based packaging films for fruit preservation by combining hydroxypropyl guar (HPG), cellulose nanocrystals (CNCs), deep eutectic solvents (DES), and anthocyanins (Anth). The films showed high moisture resistance (WCA 111.97°) and low oxygen permeability (3.01 cm³/m² day Pa), in addition to strong antimicrobial action, reducing bacterial counts to less than 10³ CFU. In the tests, fruits packaged with HCA-DES0.2 had their shelf life extended to up to 20 days, with a weight loss of less than 18%, while unpackaged fruits lost up to 34.05%. Hardness was also better preserved, with a reduction of less than 43.3%. These results indicate that the films are a sustainable and effective alternative to conventional plastic packaging.

The study developed by [Sharma et al. \(2021\)](#) evaluated the use of flaxseed protein-based coatings to extend the shelf life of minimally processed guavas. The results showed that the coatings reduced the degradation of bioactive compounds, with a 76.90% drop in the phenolic content in uncoated fruits, while in coated ones, the reduction was 61.40%. The coating also delayed the loss of firmness, with a 73% reduction in the control samples, while the coated samples showed drops of 46% and 27%, depending on the formulation. In addition, the total number of microorganisms was significantly lower in the coated samples, with a reduction of up to 88% compared to uncoated fruits. Sensorially, the coated fruits maintained better color, texture, and flavor attributes throughout storage, indicating that the flaxseed protein coating was effective in preserving the postharvest quality of guavas.

Preservation of strawberry quality through the use of active packaging with thyme essential oil encapsulated in zein nanofiber film was discussed by [Ansarifar and Moradinezhad \(2021\)](#). The incorporation of thyme essential oil (TEO) into zein nanofibers (Z) was evaluated as a solution to extend the shelf life of strawberries. Total bacterial counts were reduced by

50% and fungi and yeasts by 42%, while phenolic compounds were preserved better, with a reduction of only 20% in the Z/TEO group, compared to 32% in the control. Antioxidant activity decreased by 13.4% in treated strawberries, while in the control group, the reduction was 22.7%. In addition, titratable acidity was better preserved, with a decrease of 20.5% in the Z/TEO group, compared to 33.7% in the control group. These results indicate that the active coating delayed spoilage and increased the shelf life of strawberries.

The study developed by [Shen et al. \(2024\)](#) demonstrated that in-situ packaging based on nanofibers was highly effective in preserving cherry tomatoes, significantly reducing weight loss and maintaining fruit firmness during storage. In the evaluation of tomato preservation, in-situ packaging was highly effective in reducing gray mold infection, with fruits packaged with NAT/CMCH/PCL showing a significant reduction in the average diameter of lesions (3.7 mm) compared to fruits without packaging (14.7 mm). In addition, tomatoes with in-situ packaging showed greater firmness on days 4, 8, and 12 of storage, indicating a delay in ripening. Metabolic analysis revealed significant changes, with 230 metabolites altered, of which 38.26% were increased and 61.74% reduced. Among these, 54.84% were involved in secondary metabolite biosynthesis and 51.61% in general metabolic pathways, suggesting that packaging positively influenced the chemical stability of fruits. These results demonstrate that in-situ packaging technology can be an efficient solution to extend the shelf life of postharvest fruits.

10.4.2 Biomaterials from Fruit and Vegetable Waste for Packaging in Fruits and Vegetables

Fresh produce waste is generated during processing, such as peels, seeds, pulp, bagasse, and stems, which represent 10–35% of the gross mass ([Figure 10.6](#)) ([Ferreira et al., 2015](#)). This waste, liquid or solid, comes mainly from fruits and vegetables, such as grapes, olives, apples, citrus

fruits, potatoes, and tomatoes, and represents approximately 40–50% of the total discarded ([Dilucia et al., 2020](#)).

In this context, the use of fruit and vegetable by-products in food packaging offers a sustainable solution, reducing waste and the environmental impacts of conventional materials ([Figure 10.7](#)) ([Gupta et al., 2024](#)). By-products such as citrus peels, tomato peels, and potato starch are transformed into biodegradable films and coatings, promoting the circular economy and reducing dependence on petroleum-based plastics ([Gupta et al., 2024](#)). However, challenges such as high costs, scalability, and consumer acceptance still need to be overcome.

Fruit and vegetable waste is rich in bioactive compounds, such as simple sugars, carbohydrates, pectin, fiber, phenolic acids, carotenoids, flavonoids, and vitamins, which can be used in the manufacture of new products ([Dilucia et al., 2020](#)). Research has explored sustainable ways to reuse this waste, adding value to products such as flour or developing biodegradable coatings and films ([Brito et al., 2011](#)).

Fruit and vegetable wastes or by-products, such as pectin, cellulose, starch, and proteins, are widely used in the production of biodegradable, edible materials, which offer effective barriers against oxygen and promote sustainability ([Dilucia et al., 2020](#)).

The use of fruits and vegetables in packaging offers several advantages, such as the reuse of raw materials with reduced commercial value, including deformed or damaged fruits and vegetables, which reduces waste and lowers production costs ([Dilucia et al., 2020](#)). In addition, waste such as peels and seeds can be processed efficiently, avoiding the accumulation of easily decomposable waste ([Kumar et al., 2020](#)). There is also the potential to reduce the amount of synthetic packaging waste by partially replacing it with renewable materials ([Janowicz et al., 2023](#)). The production of packaging from fruit and vegetable puree or flour is also financially advantageous.

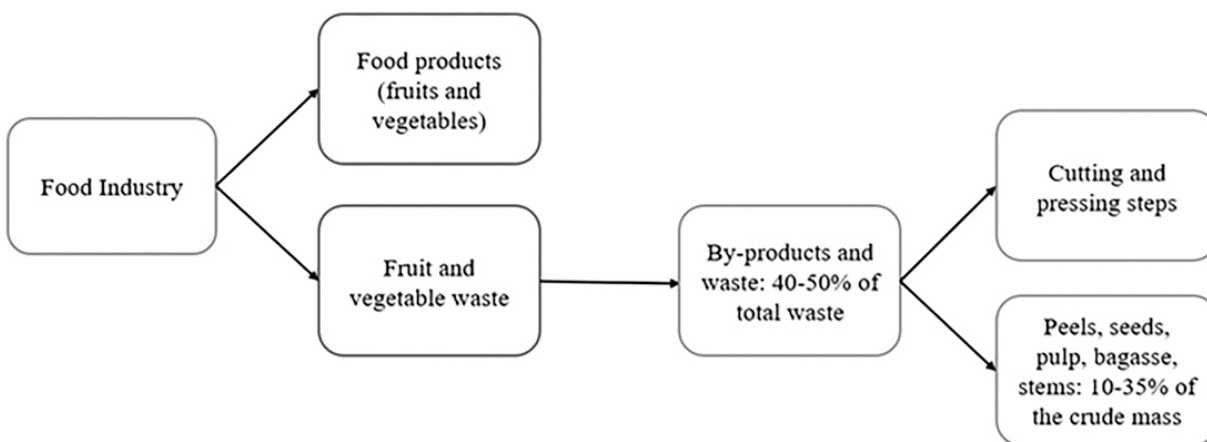


FIGURE 10.6 Waste generated in the processing of fruits and vegetables. [↗](#)

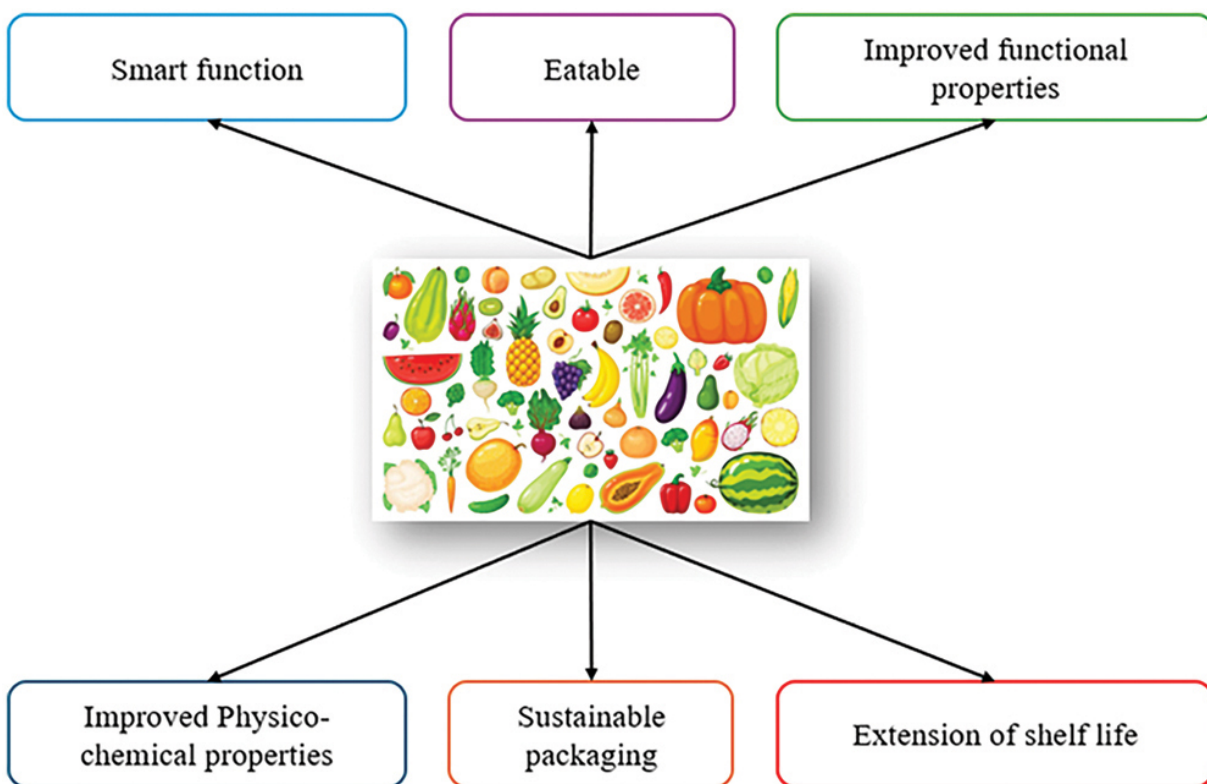


FIGURE 10.7 Application of fruits and vegetables in food packaging. [↗](#)

10.4.2.1 Fruit Peel Waste

Fruit peel waste represents a promising source for the production of biodegradable packaging, being rich in carbohydrates, fibers, and polyphenols. Proper management and conversion of this waste into eco-

friendly biopolymers not only reduces food waste but also helps to reduce dependence on conventional plastics ([Ali et al., 2024](#)). Furthermore, packaging derived from fruit peels is biodegradable and compostable, offering a sustainable alternative to single-use packaging, especially in the fruit and vegetable sectors ([Sani et al., 2023](#)).

Apple (*Malus pumila*) is a widely consumed fruit grown mainly in temperate regions. In 2018, global production was 86.14 lakh tons, with 70–75% consumed fresh and 25% processed into products such as juices and jams. The waste from apple processing, known as pomace, accounts for approximately 25% of the production, generating around 10 lakh metric tons annually in countries such as India and China, which becomes an environmental challenge. Apple pomace, composed mainly of peel and skin, can be used for the production of biodegradable packaging due to its rich composition of cellulose, hemicellulose, lignin, and pectin, in addition to having nutritional and antioxidant properties ([Liu et al., 2012](#)). [Nguyen et al. \(2022\)](#) produced biodegradable films based on passion fruit peel pectin and chitosan, incorporated with *Piper betle* L. leaf extract, aiming at applications in antimicrobial packaging. The main findings include a 42.89% reduction in the tensile strength of the films with increasing extract concentration, in addition to increased water vapor permeability. In terms of antimicrobial properties, the films showed increasing efficacy against *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Bacillus cereus*, and *Klebsiella pneumoniae* as the extract concentration increased. The film with 2.0% of the extract showed the highest antimicrobial activity, evidencing its potential to extend the shelf life of packaged fruits and vegetables. In practical application, the films were used to preserve purple eggplants and demonstrated effectiveness in maintaining soluble solids, reducing their variation to only 1.00%, compared to 3.38% in the unpackaged controls. These results highlight the potential of the films as a sustainable alternative for active packaging in food preservation ([Nguyen et al., 2022](#)).

TABLE 10.4 Studies Involving Packaging Based on Biomaterials from Fruit and Vegetable Waste 

<i>BY- PRODUCT</i>	<i>COMPONENTS USED</i>	<i>FINAL PRODUCT</i>	<i>PROPERTIES</i>	<i>REFERENC</i>
Citrus Peels	Pectin	Edible films, coatings	Biodegradable and with good barrier properties	Khalil et al (2023)
Potato Skins	Starch	Biodegradable plastics	Strong and flexible material	Taha et al (2024)
Mango Seeds	Starch	Biodegradable material	Biodegradable, strong, and with good durability	Admase et (2022)
Carrot Pomace	Fiber	Biodegradable films	Biodegradable and with good barrier properties	Merino et al (2024)
Grape Seed Extract	Pectin	Biodegradable films	Good mechanical strength, antimicrobial activity, and antioxidant properties.	Priyadarshi al. (2022)
Pineapple Peel	Alginate	Biodegradable films	Increased antioxidant and antimicrobial activity.	Lourenço et (2020)
Grape Seed Extract	Chitosan	Active movies	Better physicochemical properties	Alves et al (2018)
Kiwi Peel Extract	Pectin	Biodegradable films	Better tensile strength and	Han and So (2021)

BY- PRODUCT	COMPONENTS USED	FINAL PRODUCT	PROPERTIES	REFERENC
			Young's modulus, better water vapor permeability	
Pomace Extract	Gelatin	Active movies	Good physical and barrier properties	da Nóbreg Santos et al (2022)
Pomegranate Peel Extract	Zein	Biodegradable films	Good tensile strength and elongation, good antioxidant activity	Mushtaq et al (2018)

10.4.2.2 Fruit Seed Waste

Seeds from various fruits contain natural polymers, oils, and proteins that can be processed into bioplastics. Fruit seed-based packaging is biodegradable, compostable, and offers a promising solution in industries such as food, cosmetics, and pharmaceuticals, where environmentally friendly materials are in high demand.

A study by [Lalnunthari et al. \(2020\)](#) investigated the extraction of protein from pumpkin seeds and pectin from pumpkin peels for the development of biodegradable films for packaging applications. The results showed that the films produced had tensile strengths between 2.04 and 5.28 MPa and elongations between 13.13% and 14.37%, acceptable values for packaging applications. In addition, water vapor permeability ranged from 3.24×10^{-6} to 6.24×10^{-6} g/Pa.m.h, indicating that the films have good moisture barrier properties. In practical applications, these films can be used as

biodegradable food packaging, reducing dependence on conventional plastics and promoting the use of agro-industrial waste. However, improvements in the solubility of films may be necessary to increase their commercial viability.

Mango (*Mangifera indica*), known as the queen of fruits, consists of 33–70% pulp, 15–20% peel, and 7–24% pit, with much of the waste, such as peel and pit (35–60%), being discarded after processing ([Manju et al., 2015](#)). These wastes, rich in fiber, pectin, and starch (58% in the pit), have been used to develop edible coatings and films for food packaging. [Nawab et al. \(2022\)](#) evaluated the effectiveness of biodegradable packaging made from mango seed starch (MKS) in preserving red pepper powder (*Capsicum annuum*), comparing it with polyethylene (PE) packaging. The main findings indicate that, after six months of storage at 40°C, the loss of capsaicinoids (responsible for the pungency of the pepper) was 48.4% in PE packaging, while it was reduced to 39.3% in MKS packaging with glycerol, 27.2% in MKS packaging with plasticizer mixtures, and only 15.7% in MKS packaging with sorbitol. Regarding color retention, the loss of carotenoids was significantly lower in MKS packaging. While the pepper powder stored in PE lost 49.4% of its original color, the losses in MKS packaging were 39.2% (glycerol), 32.5% (plasticizer mixture), and only 25.2% (sorbitol).

10.4.2.3 Other Studies

[Table 10.4](#) presents several studies involving packaging based on biomaterials from fruit and vegetable waste.

The main components used are pectin, starch, fiber, alginate, and chitosan, which are extracted from different plant sources. Pectin is frequently used in biodegradable films and films, standing out for its mechanical resistance, antimicrobial activity, and antioxidant properties (such as in grape seed extract and kiwi peel) ([Han & Song, 2021](#); [Priyadarshi et al., 2022](#); [Khalil et al., 2023](#)). Starch, present in potato peels and mango seeds, provides flexibility and good durability to biopolymers

([Taha et al., 2024](#)). Fiber and alginate contribute to improving barrier properties and antioxidant activity ([Lourenço et al., 2020](#); [Merino et al., 2024](#)).

In terms of functionality, the resulting materials are biodegradable and present improved properties, such as mechanical resistance and barrier against moisture and oxygen, in addition to antimicrobial and antioxidant effects ([Khalil et al., 2023](#)). These attributes are essential for increasing the shelf life of food and reducing the use of synthetic plastics ([Mushtaq et al., 2018](#)). However, despite the benefits, large-scale implementation still faces challenges, such as cost optimization, adaptation to industrial requirements, and consumer acceptance. Continued research in this area can help overcome these barriers and consolidate the use of biopolymers in the sustainable packaging market.

10.5 LIMITATIONS AND FUTURE TRENDS OF BIOMATERIALS IN FRUITS AND VEGETABLES

Although biomaterial-based packaging has made great strides in the food industry, it remains at the laboratory research stage, and many factors hinder its practical application. For example, biodegradable active packaging materials are expensive, their preparation is not suitable for industrial production, and their safety has not been fully evaluated. On the other hand, with the growing interest in sustainable solutions in the food packaging sector, aligned with the need to prevent post-harvest fruit and vegetable losses, the future trends of biodegradable active packaging materials aim to preserve the quality of food products, as well as minimize the environmental impacts associated with the disposal of conventional plastics.

A promising trend is the extraction and use of agricultural waste for the production of biodegradable materials. The repurposing of agricultural by-products, such as polysaccharides, proteins, and lipids, to create new biodegradable polymers represents an innovative solution to reduce waste and costs associated with packaging production. Not only does this help to utilize waste resources, but it can also result in cheaper and more easily accessible materials, which is essential for making sustainable packaging a viable alternative on a large scale ([Nian et al., 2024](#)). Another important trend is the integration of active packaging with smart packaging. The combination of food quality control functionalities, such as the presence of indicator packaging and sensors, can significantly increase the effectiveness of biodegradable packaging. These systems not only extend the shelf life of food but also allow for real-time monitoring of storage conditions, such as temperature and humidity, as well as the microenvironment of the packaging, offering more precise control over food quality throughout the entire distribution chain ([Nian et al., 2024](#)).

Finally, nanocellulose (NC), including bacterial nanocellulose (BNC), cellulose nanocrystals (CNC), and cellulose nanofibrils (CNF), emerges as another interesting alternative. These materials can be incorporated as an alternative reinforcement for polymers and are suitable for coatings, such as fillers and bioactive compounds (essential oils, pigments, antioxidants, etc.) that are used to improve product quality ([Table 10.5](#)) ([Jafarzadeh et al., 2021](#); [Khalil et al., 2023](#)).

TABLE 10.5 Types of Cellulose and Their Extraction Methods 

<i>PULP TYPE</i>	<i>EXTRACTION METHODS</i>
Nanocrystalline Cellulose	Acid Hydrolysis; Enzymatic Hydrolysis; Mechanical Methods; Combined Methods
Nanofibrillated Cellulose	High-pressure; Homogenization; Microfluidization
Microfibrillated Cellulose	Acid Hydrolysis; Enzymatic Hydrolysis; Mechanical Methods; Combined Methods

<i>PULP TYPE</i>	<i>EXTRACTION METHODS</i>
Bacterial Cellulose	Fermentation
Cellulose Nanocomposites	Combination of nanocellulose with polymers or natural extracts, oils, or macromolecules

Nanofibrillated cellulose, obtained by mechanical processes such as high-pressure homogenization, has a high surface area and antimicrobial properties. Its films act as effective barriers against moisture and oxidation, increasing the shelf life of fruits and vegetables ([Dufresne, 2013](#)). In addition, it can be used in edible coatings that preserve texture and appearance. Nanocrystalline cellulose, obtained by acid hydrolysis, has high reactivity and antimicrobial efficacy due to its nanostructural size that interferes with microbial function and is applied in coatings and packaging with robust barriers ([Brinchi et al., 2013](#)). Bacterial cellulose, produced by bacterial fermentation, is highly pure, biocompatible, and porous, ideal for moisture absorption or release, and it offers antimicrobial protection ([Navya et al., 2022](#)). Microfibrillated cellulose, derived from mechanical or chemical treatments, forms transparent and resistant films, acting as a barrier to gases and moisture. It can also encapsulate nutrients, increasing the nutritional value of fruits and vegetables ([Li et al., 2022](#)). Finally, cellulose nanocomposites combine nanoscale fibers with other materials, creating strong, high-barrier, antimicrobial packaging ([Bharimalla et al., 2017](#)).

The applications of nanocellulose include mechanisms such as moisture control, antimicrobial protection, edible coatings, and nutrient preservation, which are sustainable and effective solutions to improve the quality and shelf life of fruits and vegetables. However, the use of nanocellulose requires toxicological studies due to differences in particle size and shape compared to conventional cellulose. In vitro and in vivo investigations have been carried out to evaluate its toxicity.

However, for these innovations to be successful, it will be necessary to improve the methods and techniques of packaging preparation. The industry

still faces technical challenges in developing biodegradable packaging that meets large-scale production requirements. Optimizing existing processes or creating new preparation technologies will be key to ensuring that packaging is not only efficient but also affordable for producers and consumers. In addition, the interaction between the active components and the film-forming matrix needs to be understood in greater depth. The effectiveness of biodegradable active packaging depends on the synergy between the active ingredients (such as antioxidants, antimicrobials, or ethylene absorbers) and the base material of the packaging. Further studies on these interactions will help enhance the properties of the packaging and ensure that the active compounds are released in a controlled manner without affecting the structure of the packaging ([Nian et al., 2024](#)).

Another crucial point for the evolution of biodegradable packaging materials is the evaluation of their safety. The migration of active compounds, such as embedded nanoparticles, to packaged fruits and vegetables needs to be rigorously monitored. The long-term toxicity of these materials, especially in the case of packaging containing bioactive ingredients or nanoparticles, must be carefully evaluated to ensure that there are no risks to consumer health. Studies on food safety are essential to ensure that packaging not only preserves food but is also safe for consumption. Finally, future trends in biodegradable active packaging materials are not just limited to environmental sustainability but involve a range of technological innovations that aim to improve efficiency and safety in food preservation. With the advancement of these technologies, food packaging is expected to evolve into smarter, safer, and more sustainable systems, providing benefits for both consumers and the environment.

10.6 CONCLUSION

Food packaging, especially for fruits and vegetables, plays a crucial role in preserving these products' nutritional, sensory, and microbiological quality,

and their integrity is often compromised during processing, which can accelerate deterioration processes. In addition to safeguarding sensory and dietary properties, biodegradable packaging also has the potential to meet the growing demand for solutions that minimize the environmental impacts of the food industry. Conventional preservation technologies, such as refrigeration, freezing, and chemical treatments, can be limited in terms of both effectiveness and environmental effects, in addition to being costly and energy-intensive. Therefore, the development of alternatives, such as edible films and active and intelligent packaging incorporating sustainable biomaterials, is becoming increasingly relevant.

These innovations not only allow for the long-term preservation of fruits and vegetables but also open up new opportunities for valorizing agricultural waste and creating packaging solutions from renewable resources. Using biopolymers extracted from agricultural waste, such as polysaccharides and proteins, can provide a low-cost alternative while minimizing environmental impact. Therefore, the future of fruit and vegetable packaging is intrinsically linked to innovation and sustainability. The development of biodegradable and active packaging not only meets the needs of food preservation and waste reduction but also represents an important contribution to reducing dependence on petroleum-derived plastics, providing benefits for both the food industry and the environment.

10.7 ACKNOWLEDGMENTS

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Sustainable Biomaterials for Bakery Products

11

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11.1 INTRODUCTION

In today's fast-paced lifestyle, unhealthy eating habits and high stress levels have become common, leading to the rise of chronic conditions such as obesity, diabetes, and hypertension. A balanced diet is essential for managing stress and reducing the risk of these illnesses. Among various food options, bakery products have gained immense popularity due to their wide availability, long shelf life, and convenience as ready-to-eat items ([Kumar et al., 2022](#)). However, most bakery products are packaged in plastic, contributing to significant environmental pollution. Plastics, while cost-effective and durable, pose serious challenges, including their inability to biodegrade and the harmful effects of their degradation products on ecosystems and human health. This has spurred the need for innovative solutions, such as biomaterials, to address these environmental concerns and transition toward sustainable packaging practices.

Sustainable biomaterials, derived from renewable natural resources, are gaining prominence in the bakery industry as innovative solutions for addressing environmental concerns and enhancing product quality. These materials are designed to minimize environmental impact throughout their life cycle, from sourcing to disposal ([Agnieray et al., 2021](#)). The use of synthetic materials, particularly plastics, in packaging has numerous drawbacks, including their limited lifespan, susceptibility to damage, and negative impact on the environment and human health. Plastics can easily absorb odors and flavors, and their degradation leads to environmental pollution, which has been linked to various health issues such as high blood pressure, headaches, and gastrointestinal problems. This growing concern over plastic waste has intensified global efforts toward waste reduction, with consumers becoming more aware of the environmental impact ([Akhtar et al., 2024](#)). As a result, the bakery industry faces increasing pressure to adopt sustainable practices. Packaging is a significant contributor to plastic pollution, underscoring the need for eco-friendly alternatives that support a circular economy and reduce reliance on non-renewable resources.

The shelf life of baked goods is influenced by factors such as staling, moisture loss, and microbial growth. Staling, primarily caused by starch retrogradation, leads to undesirable textural changes in the crumb, while moisture loss compromises sensory quality ([Sluková et al., 2015](#)). Microbial spoilage, particularly mold growth, along with lipid and protein oxidation, further restricts the shelf life of these products due to their high water-activity and poses potential health risks ([Estévez et al., 2017](#)). Although preservatives like propionic acid and ethanol emitters can mitigate microbial growth, their use raises consumer acceptance issues, such as labeling concerns and potential off-odors ([Melini & Melini, 2018](#)). Additionally, traditional double plastic film layers, though effective, contribute to environmental pollution as they are non-biodegradable ([Kabir et al., 2020](#)). These challenges emphasize the need for innovative solutions to enhance the shelf life and quality of bakery products while reducing environmental impact.

Bioplastics such as PLA, PBAT, and thermoplastic starch have emerged as promising candidates for sustainable bakery packaging. Advances in material blending have enhanced their physical, mechanical, and barrier properties, while incorporating natural antimicrobial agents like carvacrol has expanded their functionality. Studies show that active packaging, such as cellulose acetate films with sodium propionate, gliadin films with cinnamaldehyde, and methylcellulose films with clove and oregano essential oils, can extend the microbial shelf life of baked products. Chitosan (CH), an amino polysaccharide known for its antimicrobial properties, biodegradability, film-forming ability, and high gas permeability, is ideal for active packaging. Carboxymethyl cellulose (CMC), a cellulose derivative, offers excellent barrier properties against oxygen and lipids and forms transparent films, improving consumer appeal. When combined, CH and CMC form strong ionic cross-linking bonds, making them biocompatible and effective for packaging. These materials not only extend shelf life and maintain freshness but also reduce food waste and minimize the environmental footprint of conventional packaging in the bakery sector ([Noshirvani et al., 2017](#)).

By aligning with the UN Sustainable Development Goals, sustainable biomaterials not only help reduce carbon emissions and plastic waste but also meet growing consumer demand for cleaner, eco-friendly products. This chapter will focus on the use of sustainable biomaterials in bakery packaging, including their applications in both edible and non-edible packaging solutions. It will explore innovative approaches such as biodegradable packaging, edible films, and active packaging technologies. Additionally, the chapter will address challenges related to the incorporation of these materials in packaging, including compatibility with bakery products, cost, scalability, and consumer acceptance. The environmental benefits of using sustainable biomaterials in packaging will also be discussed, along with prospects for their widespread adoption in the bakery industry.

11.2 FACTORS AFFECTING SHELF LIFE OF BAKERY PRODUCTS

Bakery products are integral to global diets, with bread being among the most widely consumed items. However, their perishability poses significant challenges, as spoilage can occur due to physical factors (such as moisture migration and staling), chemical factors (such as rancidity), and microbiological factors (such as the growth of fungi and yeasts). These changes compromise the sensory quality, safety, and shelf life of bakery products, leading to food waste and economic losses ([Smith et al., 2004](#)). To address these issues, continuous advancements in packaging, preservation techniques, and ingredient formulations are essential to ensure product quality and reduce spoilage.

11.2.1 Physical Factors

Physical spoilage contributes to quality degradation, with moisture migration between the crumb, crust, and packaging materials being a significant concern. These changes not only accelerate staling but also compromise texture and sensory appeal. The retrogradation of starch components leads to staling, resulting in moisture loss and increased firmness in breadcrumbs. Water activity plays a critical role in determining texture, with higher moisture content providing softness and lower moisture content leading to hardness. In addition to water activity, the water vapor permeability of packaging materials influences moisture migration. This characteristic affects relative humidity and product stability during storage, as higher permeability allows for faster moisture transfer, contributing to changes in crumb hardness due to water loss. Studies have demonstrated a linear relationship between water vapor permeability and crumb hardness in biodegradable films, with higher permeability facilitating moisture migration and reducing water activity over time ([Bumbudsanpharoke et al., 2022](#)).

Bread aging is another major contributor to global food waste, with significant environmental and economic impacts. Research has shown that managing crumb moisture loss and minimizing the moisture gradient between the crumb and crust can mitigate aging and enhance the perception of softness ([Dong & Karboune, 2021](#)). To mitigate spoilage and extend shelf life, food producers adopt various strategies, including (a) inactivation of microorganisms through heat treatments or chemical preservatives; (b) inhibition of microbial growth using preservatives, modified atmosphere packaging, and optimized storage conditions; and (c) prevention of contamination via improved packaging and hygienic handling practices ([Hernández et al., 2018](#)). Effective packaging solutions are crucial for addressing these challenges.

11.2.2 Chemical Factors

Chemical spoilage, including lipid oxidation and protein degradation, impacts the sensory and nutritional quality of bakery products ([Figure 11.1](#)). Oxidation leads to off-flavors and a loss of texture, particularly in products with high-fat content ([Smith et al., 2004](#)). Rancidity occurs due to lipid oxidation, driven by storage time, low water activity, and oxygen permeability in packaging materials. High porosity in bakery products traps residual oxygen, accelerating oxidation. Oxygen scavenging packaging is critical to reduce oxygen levels and minimize oxidation. Products with low water activity (under 0.3) are prone to rapid oxidation, which decreases at higher water activity (0.5) before rising again. Ingredients with naturally high fat content, such as nuts and oats, can act as sources of free radicals, promoting oxidation. Lipase enzymes can remain active even at low water activity (0.25), creating further challenges for stability. These processes are influenced by intrinsic factors, such as ingredient composition, and external factors, like storage conditions. Intrinsic factors, including water activity, pH, redox potential, and nutrient composition, significantly affect microbial growth. For example, while nutrients in raw materials may promote microbial proliferation, specific additives like fats and salts can enhance

shelf life ([San et al., 2022](#)). External factors, such as temperature and humidity, also play a pivotal role in determining product stability. Spoilage microorganisms are classified based on their temperature preferences: thermophiles, mesophiles, psychrophiles, and psychrotrophs, with mesophiles (optimal growth around 37°C) including many foodborne pathogens ([Šmídová & Rysová, 2022](#)).

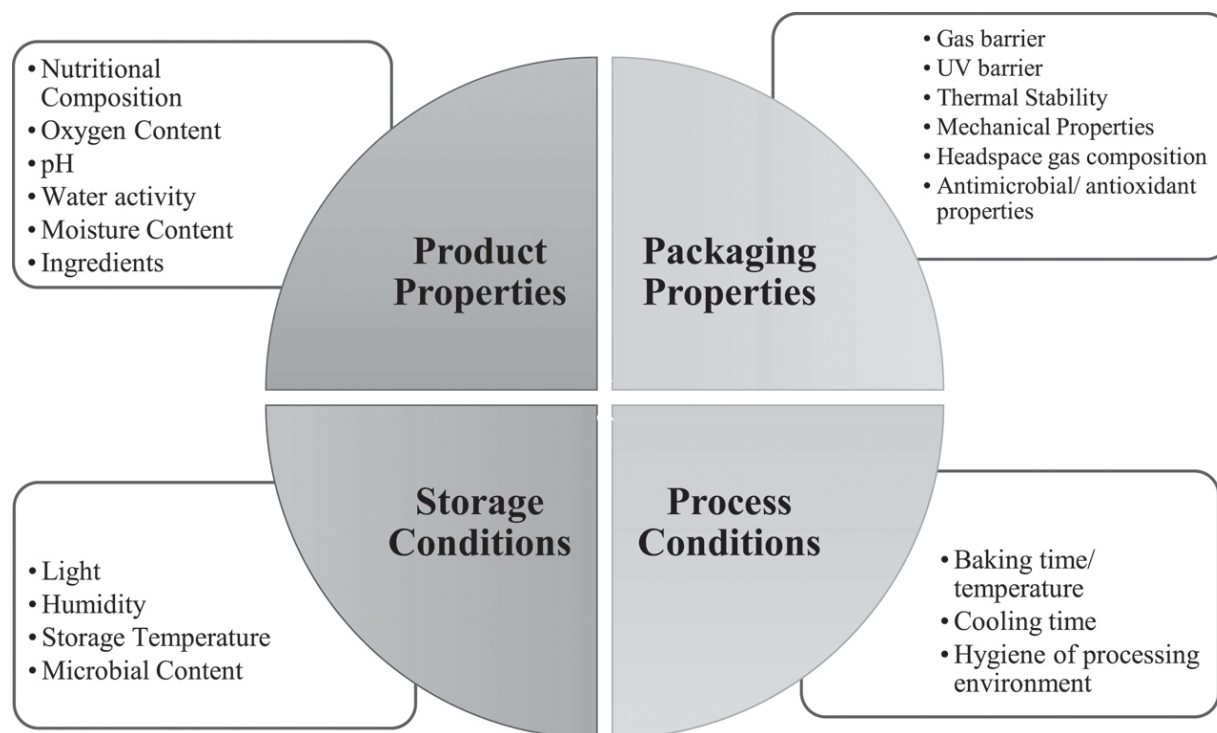


FIGURE 11.1 Major factors affecting shelf life of bakery products. [↗](#)

11.2.3 Microbiological Factors

Microbiological spoilage is a significant issue for bakery products, reducing shelf life and causing economic losses for manufacturers and consumers due to poor packaging, inadequate sanitation, improper storage, and low product turnover ([San et al., 2022](#)). Microorganisms can be introduced through raw materials, contamination during processing or packaging, or after baking. Fungal spoilage is common in wheat-based bakery products, with species like *Penicillium*, *Aspergillus*, *Cladosporium*, and *Rhizopus stolonifer* being common spoilage agents ([Subramaniyan et al., 2022](#)). Mold

growth is particularly problematic in low-humidity environments, with mycotoxin production as an additional concern. Other fungi, such as *Eurotium* and *Mucor*, also contribute to spoilage, and losses can range from 1% to 5%, depending on factors like weather, product type, and processing ([San et al., 2022](#)).

Molds, yeasts, and bacteria all contribute to spoilage in bakery products. Molds such as *Rhizopus stolonifer*, *Penicillium*, and *Aspergillus* produce harmful mycotoxins, while yeasts like *Hyphopichia burtonii* and *Saccharomycopsis fibuligera* cause “chalk mold,” releasing mycotoxins before visible fungal growth occurs ([Garcia et al., 2019](#); [Subramaniyan et al., 2022](#)). Yeasts like *Saccharomyces* and *Trichosporon variable* cause spoilage in bakery products, with *Saccharomyces* sp. leading to “chalk bread” ([Axel et al., 2017](#)). Rope spoilage in bread is caused by bacteria such as *Bacillus subtilis*, *Bacillus licheniformis*, and *Bacillus cereus* ([San et al., 2022](#)). Yeasts contribute to spoilage by growing on surfaces and producing off-flavors through fermentation. *Bacillus subtilis* spores can survive the baking process, compromising product safety, and *Staphylococcus aureus* contamination in cream-filled products can lead to food poisoning outbreaks ([Li et al., 2012](#); [Gigante et al., 2023](#)).

Studies have shown that mold growth in bread is primarily influenced by post-baking contamination rather than the baking process itself, as mold spores are typically destroyed during baking ([San et al., 2022](#)). Oxygen permeability in packaging can also contribute to microbial growth by allowing the growth of aerobic organisms like molds, while water vapor permeability (WVTR) plays a crucial role in microbial growth at intermediate water activity levels. Moisture loss due to high WVTR reduces water activity, inhibiting microbial growth and particularly affecting bacterial growth ([Bumbudsanpharoke et al., 2022](#)).

11.2.4 Storage Conditions

Temperature is a key factor in bread and bakery spoilage, as microorganisms grow within specific temperature ranges: bacteria thrive

around 35°C, and molds at approximately 30°C. Effective processing methods, such as baking, chilling, and freezing, disrupt microbial growth, baking eliminates pathogens with high heat, chilling slows microbial metabolism, and freezing halts growth entirely ([Santos et al., 2017](#)). Humidity also influences spoilage by driving moisture transfer between the product and its environment. High ambient humidity fosters mold growth, while poor packaging can cause staling due to moisture loss. Similarly, the gaseous composition of the storage environment impacts spoilage. Air supports microbial proliferation, whereas modified atmospheres (e.g., carbon dioxide or nitrogen-rich) inhibit growth, highlighting the need for packaging with strong gas barrier properties ([Licciardello et al., 2017](#)).

Addressing the combined effects of microbial, chemical, and physical spoilage is crucial for maintaining the quality, safety, and sustainability of bakery products. Advanced approaches, such as incorporating antimicrobial agents into packaging materials or using edible coatings, are gaining traction in industry. By leveraging advanced packaging technologies, adopting eco-friendly materials, and optimizing storage and handling practices, the bakery industry can reduce food waste and meet consumer expectations for high-quality, safe, and sustainable products.

11.3 PRESENT-DAY TECHNIQUES IN BAKERY PACKAGING

The primary objectives of packaging bakery products are to prevent microbial contamination, preserve sensory attributes, and maintain optimal humidity levels. Effective packaging plays a crucial role in extending the shelf life of bakery items, which are inherently prone to spoilage due to factors such as moisture loss and microbial growth. Packaging solutions vary depending on the shelf life and types of bakery products. For products with a short shelf life, such as fresh bread (1–2 days), paper bags or perforated foils are commonly used. These materials provide basic

protection but are typically not sufficient for longer storage. Sliced and specialty breads, with slightly longer shelf lives, are often packaged in polyethylene (PE) bags, including low-density (PE-LD) and linear low-density polyethylene (PE-LLD) variants, offering moderate protection against moisture and air. For products requiring extended shelf life, polypropylene (PP) heat-shrinkable or extensible foils are preferred due to their ability to act as effective barriers to moisture and gases. These materials are also heat-resistant, making them ideal for packaging hot or thermally processed bakery products. High-value items such as delicacies and semi-confectionery products are typically packaged in multi-layer foils, like polyamide/polyethylene or combinations of different polyethylene types (e.g., PE-HD/PE-LD), providing enhanced protection and durability. By choosing appropriate packaging materials and technologies, manufacturers can significantly improve preservation, reduce spoilage, and address consumer demand for freshness ([Kwaśniewska et al., 2014](#)).

In addition to traditional packaging methods, various advanced techniques have been developed to extend the shelf life of bakery products. Modified Atmosphere Packaging (MAP) is a vital technology for enhancing the longevity of bread and other bakery items. This method involves replacing the air inside the package with a mixture of inert gases, typically carbon dioxide and nitrogen, which slows down staling and inhibits microbial growth. By reducing oxygen exposure, MAP creates an environment that is less conducive to mold and fungal growth. Carbon dioxide has fungistatic properties that disrupt the metabolism of fungal cell membranes, preventing mold formation and extending shelf life. The specific gas mixture used in MAP can vary, with each combination designed to achieve a particular shelf-life extension for bakery products ([Garcia & Copetti, 2019](#)).

Microperforated flow pack packaging is an effective technique for extending shelf life, as it incorporates small perforations to regulate airflow. This allows for controlled moisture exchange, preventing excess moisture accumulation that can promote mold growth, while maintaining balanced humidity levels within the product. Additionally, sustainable coatings

applied to packaging surfaces help reduce moisture and gas migration, further enhancing packaging performance. A study demonstrated the successful development of an active packaging solution using cinnamon essential oil combined with micro-perforated polypropylene, which extended the shelf life of a bakery product from 3 to 10 days while maintaining its quality and safety. This approach required minimal changes to existing packaging processes, making it a practical solution for real-world applications. The sensory evaluation method developed can be adapted for various bakery products, providing a standardized way to assess packaging performance. These results suggest that essential oil-based active packaging could offer a sustainable alternative to conventional preservation methods by enhancing both shelf life and product quality. Further industrial-scale studies are expected to bring this solution to market ([Gutierrez et al., 2009](#)).

Antimicrobial packaging is also increasingly utilized in the bakery industry. This type of packaging incorporates active agents such as oxygen scavengers, moisture absorbers, or antimicrobial substances that inhibit microbial growth, ensuring the safety and quality of the products. Oxygen scavengers, like the “Ageless” preparation, are commonly used in active packaging. These scavengers can significantly extend the shelf life of bakery products, such as rolls, by removing oxygen from the package and preventing mold growth ([Yi & Kerr, 2009](#)). Furthermore, active packaging can include natural antimicrobial substances such as essential oils or oleoresins derived from spices and herbs. These compounds, which have been shown to possess antibacterial and fungistatic properties, are incorporated into the packaging without altering the taste or aroma of the products. For instance, white mustard oil, which contains allyl isothiocyanate, is a potent antifungal agent that can extend the shelf life of bread without compromising its sensory qualities ([Kwaśniewska et al., 2014](#)).

The combination of MAP with active packaging technologies provides a highly effective solution for extending the freshness, safety, and quality of bakery products. By integrating these modern packaging techniques,

manufacturers can better meet consumer demands for fresh, safe, and high-quality bakery items, all while addressing sustainability concerns in food packaging.

11.4 BIOMATERIALS IN PACKAGING OF BAKERY PRODUCTS

Biomaterials are gaining significant attention in the packaging of bakery products due to their sustainable and eco-friendly characteristics. Derived from natural, renewable resources, biopolymers and bioplastics offer promising alternatives to conventional plastics. These materials are not only biodegradable, reducing the environmental impact of packaging waste, but they also contribute to improving food safety and extending the shelf life of baked goods. By integrating biomaterials into packaging solutions, the food industry can address both the demand for functional, protective packaging and the growing need for environmentally responsible options. Various studies on biomaterials utilized for the development of packaging of bakery products have been presented in [Table 11.1](#).

11.4.1 Biopolymers

Biopolymers, natural polymers derived from renewable sources such as plants, animals, and microorganisms, are increasingly favored in the food packaging industry due to their biodegradability, environmental sustainability, and functional versatility. These materials include polysaccharides (e.g., starch, cellulose, chitosan, alginate, and lignin), proteins (e.g., whey protein, casein, gelatin, wheat gluten, silk, and wool), and lipids (e.g., beeswax, fatty acids, plant oils, and animal fats). Additionally, natural rubber and certain polyesters produced by microorganisms or plants (e.g., polyhydroxyalkanoates, poly-3-hydroxybutyrate) or synthesized from bio-derived monomers (e.g.,

polylactic acid (PLA)) also fall within the biopolymer category. Their ability to offer excellent barrier properties, biocompatibility, non-toxicity, and renewable sourcing makes them ideal for sustainable food packaging solutions ([Song et al., 2009](#)). Their application in bakery product packaging is driven by their outstanding barrier properties against moisture, gases, and oxygen—critical factors for extending shelf life and maintaining product quality. Biopolymers also exhibit strong intermolecular hydrogen bonding and a polar nature, which impedes the diffusion of apolar molecules such as oxygen and carbon dioxide, further enhancing their packaging performance ([Coltelli et al., 2015](#)).

Biopolymers are applied in various forms, such as coatings, films, blends, and bio-nanocomposites, tailored to specific packaging needs. These materials not only enhance the mechanical and barrier properties of packaging but also reduce reliance on traditional plastics, aligning with sustainable development goals. However, challenges such as hydrophilicity, brittleness, and limited mechanical strength restrict their large-scale application. To address these issues, modifications such as blending with other materials, incorporation of nanofillers, and chemical treatments are employed, resulting in improved durability and functionality ([Mujtaba et al., 2022](#)). Advanced applications of biopolymers have shown promising results in improving packaging performance. Materials like cellulose nanocrystals, chitosan, biopolyesters, and modified starches have been successfully used as coating materials to enhance the barrier properties of paper and cardboard packaging ([Rastogi & Samyn, 2015](#)).

Several studies have explored the use of biopolymers in food packaging to extend shelf life and improve food quality. [Gregirchak et al. \(2020\)](#) developed an edible coating containing lactic acid bacteria, sodium alginate, whey, and glycerol for wheat bread, which protected the bread from microbial spoilage by reducing the growth of mesophilic bacteria and fungi such as *Aspergillus* and *Penicillium*. Similarly, [Altamirano-Fortoul et al. \(2012\)](#) applied a probiotic coating incorporating *Lactobacillus acidophilus* and starch-based materials on baked bread, which enhanced protection while maintaining sensory quality. In another study, [Bartolozzo et al. \(2016\)](#)

utilized triticale flour to coat muffins, which successfully delayed crumb firming and kept the muffins softer for longer, reducing weight loss during storage. [Senanayake \(2021\)](#) employed okra mucilage for biscuit coating, which not only improved moisture barrier properties but also reduced microbial spoilage, preserving the product’s crispness. Additionally, [Noshirvani et al. \(2017\)](#) developed a composite active coating using chitosan, carboxymethyl cellulose, oleic acid, and zinc oxide nanoparticles to extend the shelf life of sliced bread by maintaining moisture content and limiting water vapor permeability. [Lastly, Saraiva et al. \(2016\)](#) created edible coatings from potato starch, inverted sugar, and sucrose to control the release of citric acid and potassium sorbate, effectively preserving the shelf life of mini panettone. These studies demonstrate the potential of biopolymer-based coatings and films in improving food preservation through antimicrobial activity, moisture control, and extended freshness. These innovations not only support sustainability but also provide effective solutions for maintaining food safety and extending the shelf life of bakery products.

TABLE 11.1 Biomaterials and Their Applications in Bakery Product Packa

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLIC</i>
Cellulose-glycerol films, Trifluoroacetic acid, Trifluoroacetic anhydride	Biodegradable films	Glycerol enhanced grease resistance while keeping low migration levels	Sponge
Cassava starch-based biodegradable films with natural antimicrobial ingredients (clove and cinnamon powders)	Prepared using casting technique	Tensile strength (TS): reduced with the addition of clove and cinnamon	Sliced

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACK/APPLIC</i>
		• % Elongation (E): lower than the control • Water vapor transmission (WVT): reduced by clove and cinnamon addition • Antimicrobial effect: not clearly determined due to increased water activity during storage	
Turmeric essential oil-based added cornstarch and pectin extract films	Edible packaging	• No visible contamination was detected during the nine weeks of analysis	Sliced
Cornstarch and pectin films incorporated with turmeric essential oil (TEO)	Manufactured using solution casting method with 3% TEO	• Good antioxidant and antimicrobial activity • Presence of active constituents like turmerone, Ar-turmerone, and β-turmerone	Sliced

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATION</i>
		• Increased mechanical strength, reduced flexibility • Transparency, solubility, WVP, and thermal stability unchanged • No contamination detected in sliced bread for nine weeks	
Blend of xanthan, bovine collagen, and oregano essential oil	Cryo-structured composite coating	• Composite coating showed significant antifungal effect, extending the shelf life of the biscuits after 15 days of storage.	Biscuits
Chitosan and beeswax-coated cellulose	Lipid-hydrocolloid emulsion coating	• Better analytical and microbiological attributes than LDPE • Reduced yeast and mold count as compared to uncoated paper	Whole bread

BIOMATERIALS	NATURE OF PACKAGING	PROPERTIES	PACKAGING APPLICATIONS
		Microbiologically stable up to 8 ± 1 days at 25°C and 12 ± 1 days at 5°C	
Sago starch (<i>Metroxylan sago</i>) modified with polyvinyl alcohol (PVA) and citric acid as an antimicrobial agent	Optimized ratio: 5:8:15 (% , w v ⁻¹) for starch: PVA: Citric acid	- Inhibited 98–99% of <i>Salmonella typhimurium</i>, <i>Escherichia coli</i> O157:H7, <i>Listeria monocytogenes</i>, <i>Aspergillus</i> spp., and <i>Rhizopus</i> spp. - Extended food shelf life: 10 days for cake, 40 days for bread	Cakes and bread
Acetylated cassava starch films incorporated with maltol (1–10%)	Active biodegradable films for bakery products	- Chemical interaction: H-bonding between starch and maltol - Smooth microstructure at up to 3% maltol, non-homogeneous matrices at higher concentrations	Preservative-free buttermilk

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		• TS and EB reduced by 37% and 34%, respectively, with 10% maltol • Hydrophilicity and molecular mobility influenced water vapor and oxygen permeability • Inhibited mold growth (6×) for butter cakes up to 19 days with 10% maltol	
Alginate + sulfur quantum dots (SQD)	Functional composite film via solution casting method	• SQDs improved the UV barrier (82%) and tensile strength (18%) of alginate films without affecting elastic modulus (EM) or water vapor permeability (WVP) • SQD-added films showed strong antibacterial activity against <i>E. coli</i> and <i>L.</i>	Bread packaging

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		<i>monocytogenes</i> and antifungal activity against <i>A. niger</i> and <i>P. chrysogenum</i> • In bread packaging, SQD films prevented mold growth for 14 days, outperforming ES and SNP films	
Potato starch + Nanodispersed titanium dioxide powder	Antimicrobial biodegradable packaging	• 1% TiO₂ in biodegradable packaging inhibited the growth of <i>E. coli</i> and <i>Bacillus subtilis</i>, showing antimicrobial properties • Packaging with 1% TiO₂ demonstrated reduced vapor permeability, while higher concentrations (2–5%) increased vapor permeability from 4.7 to 5.2 mg/(m·h·kPa)	Sliced products, restau

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
PLA + Chitosan nanoparticles (CSNPs) modified with polyethylene glycol methyl ether methacrylate (PEGMA), stearyl methacrylate (SMA) and deoxycholic acid (DC)	Active bioplastic packaging with antioxidant and antimicrobial additives	- Modified chitosan nanoparticles showed antioxidant and antimicrobial properties - CSNPs-g-pSMA exhibited 95.33% inhibition of <i>E. coli</i> and >98% inhibition of <i>S. aureus</i> - Modified CSNPs (4% wt) maintained O₂ permeation within standard food packaging limits and improved PLA elongation at break	Sliced Bread
Cornstarch (CS) bionanocomposite films incorporated with chitosan (CH), nanoclay, and varying ratios of grapefruit seed extract (GFSE)	Prepared with different GFSE ratios (0–2% v/v)	- Crystallinity: increased with GFSE up to 1.5% v/v - Tensile strength (TS): increased with GFSE up to 1.5% v/v	Bread

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		• Elongation at break (EB): decreased with GFSE addition • Film strength (FS) and water vapor permeability (WVP): Decreased with GFSE addition • At 2% v/v GFSE: Physical properties reduced • Shelf life increased: 20 days with 1.5% v/v GFSE film vs. 6 days with synthetic plastic	
Gelatin nanocomposite emulsion (GNE) films with ZnO nanoparticles	Surface coating	• Addition of nanoparticles reduced water vapor permeability from 9.68×10^{-10} to 6.07×10^{-10} g/m·s·Pa and oxygen permeability from 39.26 to 29.65 cm³/μm·m²·dkPa in gelatin	Sponge

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		nanocomposite films • GNE films showed the highest barrier properties • GNE films maintained cake acidity and peroxide values • Nanoparticles in GNE films reduced fungal growth, enhancing shelf life • Cakes in GNE films had better organoleptic and texture acceptability than other packaging films. • GNE films effectively prevent fungal growth and preserve chemical and organoleptic quality of sponge cakes without preservatives	

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
Modified cornstarch with tomato powder	Edible coating	Increases specific volume and enhances texture	Bread Frozen
Chitosan (C)-natamycin (N) film	Active + Vacuum (V) packaging	- Shelf-life extension: 6 days (control), 12 days (vacuum), 14 days (VN), 16 days (VC), 17 days (VCN) - VCN treatment extended shelf life by 11 days compared to control - Chitosan and natamycin combination reduced microbial counts (1–3 log CFU/g) for various species (mesophilic, yeasts, molds, psychrotrophic bacteria, lactic acid bacteria, <i>Enterobacteriaceae</i>,	Phy (unleashed pastry)

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		<i>Enterococci</i>) by day 18 • Combination of chitosan and natamycin preserved freshness, appearance, and sensory qualities while delaying spoilage	
Starch film + ϵ-poly-L-lysine	Antimicrobial packaging	• ϵ-PL biofilms inhibited fungal growth in solid medium at concentrations >1.6 mg/cm² • Bread shelf life increased by 1 day with 1.6–6.5 mg ϵ-PL/cm² for <i>A. parasiticus</i> and 3 days with 6.5 mg ϵ-PL/cm² for <i>P. expansum</i> • Aflatoxin production was reduced by 93–	Bread

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATION</i>
		100% using ϵ-PL biofilms ϵ-PL biofilms showed potential as a natural antimicrobial alternative to synthetic preservatives for bread storage	
Modified cellulose-based plain paper with nanoparticles	Paper sheet	- Higher photocatalytic abilities - Better wettability properties - Low air permeance	Bread
Chitosan/carboxymethyl cellulose films with oleic acid and ZnO nanoparticles	Surface coating	- Enhances microbial and physicochemical shelf life - WVP decreased from 8.27×10^{-7} to 5.28×10^{-7} g/m²·h·Pa with oleic acid, and to 1.96×10^{-7} g/m²·h·Pa with	Sliced bread

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
		2% ZnO NPs ($P < 0.05$) - Active coatings improved moisture retention, reducing water activity and staling - Control bread showed highest firmness after 15 days, indicating more staling - Microbial shelf life increased from 3 to 35 days with 2% ZnO NPs coating - Coatings with 1% and 2% ZnO NPs reduced fungal growth and microbial counts during 15 days	
Thermoplastic cornstarch with chitosan and rosemary extracts	Sachet	- Decreases yeast growth - increase antioxidant activity	Bread

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACKAGING APPLICATIONS</i>
Potato starch-based edible films	Surface coating	Increased shelf life (up to 130%) and may contribute to product loss reduction during storage	Mini Packaging
Allyl isothiocyanate-based active packaging	Sachet	Inhibited the growth of <i>A. parasiticus</i> and the production of Aflatoxin after 30 days storage	Fresh Produce
Potassium sorbate-added thermoplastic starch and butylene adipate-co-terephthalate (PBAT)	Biodegradable films	The active films inhibited microbial growth	Fresh Produce
Emulsified edible film composed of cornstarch, methylcellulose (MC), and soybean oil	Edible coating applied via spreading or spraying methods	Water vapor permeability (WVP): lower in spread film; increased with higher atomization pressure and thickness	Bakery Products (e.g., croissants)

<i>BIOMATERIALS</i>	<i>NATURE OF PACKAGING</i>	<i>PROPERTIES</i>	<i>PACK/APPLIC</i>
		• Tensile strength (TS): better in spread film • Elongation at breaking (E): dependent on application method • Film thickness: 30 μm • Moisture resistance: higher resistance to water vapor transmission (r) in coated products	

11.4.2 Bioplastics

Biocomposites are materials made by combining biopolymers with reinforcing agents, such as natural fibers, to enhance their mechanical properties and performance. In food packaging, biocomposites offer an attractive alternative to synthetic composites by improving the strength, flexibility, and durability of biopolymers, while maintaining their eco-friendly and biodegradable characteristics. Natural fibers like cellulose, flax, and hemp are often incorporated into biopolymers, resulting in packaging materials that exhibit improved barrier properties, such as resistance to moisture and gas permeation. Biocomposites are gaining traction in bakery product packaging due to their ability to provide stronger, more versatile materials that are both sustainable and effective in preserving

food quality, making them a viable solution to replace conventional fossil-based packaging materials ([Andrew & Dhakal, 2022](#)).

Innovations in this field include cellulose-based films, which offer moisture control and transparency, making them ideal for visually appealing bakery products. Bioplastics derived from renewable resources such as cornstarch not only maintain product freshness but are also compostable. In one study, five bio-based packaging materials were evaluated for their impact on the quality of fully baked frozen bread products, including hot dog and hamburger buns, in comparison to conventional polyethylene (PE) packaging. Bio-PE emerged as a promising alternative, maintaining quality parameters such as weight loss, crust and crumb hardness, springiness, and visual appeal on par with PE packaging. Panelists found no significant sensory differences between hotdog buns packed in bio-PE and those in PE. However, materials like Biodolomer®, PLA, and PBSA showed higher weight loss and drier edges, linked to their higher water vapor transmission rate (WVTR). Paper/bio-PET packaging showed potential in reducing weight loss and dry edges but faced challenges with crumb texture and product visibility, highlighting WVTR as a critical factor in preserving bread quality ([Putranda, 2017](#)).

Another study thermoplasticized bread waste with glycerol and blended it with poly(butylene adipate-co-terephthalate) (PBAT) in varying ratios to create films exhibiting excellent mechanical, thermal, and moisture-resistance properties. The incorporation of PBAT-grafted maleic anhydride as a compatibilizing agent enhanced the blends' performance, achieving optimal results with up to 40% bread waste content. This proof of concept demonstrated the feasibility of converting food waste into functional bioplastics for consumer bags, food packaging, and agricultural mulch films, significantly contributing to food waste reduction and environmental sustainability ([Bouzidi et al., 2024](#)). The shift to biodegradable packaging not only addresses environmental concerns but also presents opportunities for innovation in material science. As bakeries adopt these solutions, they can reduce their ecological footprint while meeting consumer expectations for sustainable practices.

11.5 FUNCTIONAL PROPERTIES OF BIOMATERIALS

In the following subsections, this chapter discusses advancements in the use of biomolecules to enhance sustainable packaging for bakery products. These biomolecules provide functional properties such as improved oxygen and water vapor barriers, antimicrobial activity, antioxidant effects, and preservative capabilities.

11.5.1 Barrier Properties

Barrier properties are critical in food packaging as they protect products by preventing the ingress or egress of penetrants such as water vapor, oxygen, carbon dioxide, grease, and oils, thereby preserving the quality and safety of food products. For short-term retail applications such as pizza, burgers, cookies, and similar products, grease resistance and water hydrophobicity are the key barrier properties required to maintain food quality and prevent premature degradation during handling and transportation. These properties ensure that bakery items maintain their desired characteristics, such as freshness, texture, and flavor, by creating a controlled environment inside the package. Factors influencing barrier effectiveness include the material's thickness and crystallinity, the size and polarity of the permeant, and external conditions such as temperature and humidity. The interaction between packaging materials and permeant molecules, governed by cohesive energies, plays a crucial role in determining transmission rates. When cohesive energies between the barrier wall and permeant molecules are low, the permeation rate increases, allowing unwanted substances to enter or escape. On the other hand, high cohesive energies result in reduced permeation, which is desirable for maintaining product quality. While paper-based packaging often exhibits limited barrier capabilities, offering permeability to gases, water vapor, and liquids, synthetic polymers such as polyethylene (PE), polypropylene (PP), and ethylene vinyl alcohol (EVOH)

offer superior resistance to these penetrants, which is crucial in food packaging applications. However, environmental concerns regarding these petroleum-based materials, including issues with recycling and biodegradability, have led to significant research into biopolymer alternatives. These biopolymers, derived from renewable resources, can be integrated into packaging materials to enhance their barrier properties while maintaining a sustainable, eco-friendly approach ([Tyagi et al., 2021](#); [Mujtaba et al., 2022](#)).

In food preservation, oxygen plays a critical role due to its high reactivity, which can cause the oxidation of food components such as fats and proteins, resulting in rancidity and degradation of flavor. Therefore, incorporating oxygen barrier layers into packaging is an essential strategy to extend the shelf life of bakery products. Historically, materials like poly(ethylene-co-vinyl alcohol) (EVOH) and poly(vinylidene chloride) (PVDC) have been extensively used for their excellent oxygen barrier properties ([Heras-Mozos et al., 2018](#)). However, these materials have limitations: EVOH is highly sensitive to moisture, making it vulnerable to water vapor, which necessitates its placement in multilayer packaging systems with protective outer layers of polyolefins or polyesters ([Heras-Mozos et al., 2018](#)). PVDC, on the other hand, is sensitive to temperature changes, which can lead to the degradation of its optical and mechanical properties. Despite these challenges, the integration of EVOH layers in fossil-based plastics like polyethylene and polyamides remains a proven strategy for providing high-performance packaging solutions for bakery products ([Beitzen-Heineke et al., 2017](#)).

Recent advancements in active packaging have also led to innovations in improving barrier properties. Active packaging refers to packaging systems that incorporate functional substances such as oxygen scavengers or moisture regulators, which interact with the food product to extend its shelf life and maintain freshness ([Gutierrez et al., 2009](#)). For instance, oxygen scavengers are commonly used to reduce oxygen levels within the package, inhibiting microbial growth and slowing down oxidative reactions that contribute to spoilage. Hydrophilic matrices in controlled delivery systems

allow for the incorporation of active agents like antimicrobials and preservatives into polymer-based films, maintaining high concentrations of these active substances in contact with the food surface. These innovative packaging materials can effectively reduce microbial growth, preserve the sensory properties of bakery products, and extend shelf life ([Benitez et al., 2024](#)). A study explored the development of bio-based functional materials for active packaging by extruding thermoplastic starch (TPS) and linear low-density polyethylene (LLDPE) blends with pyrogallol (PG) as an oxygen scavenger. PG improved polymer compatibility, modified microstructure, and reduced crystallinity, enhancing oxygen absorption rates based on PG content and temperature. The material's mechanical properties and oxygen scavenging capacity make it suitable for sustainable packaging of oxygen-sensitive products, highlighting its potential as an eco-friendly biomaterial ([Promsorn & Harnkarnsujarit, 2022](#)).

In addition to synthetic polymers, recent research has highlighted the potential of biopolymer-based materials in enhancing the barrier properties of packaging. Protein-based films, such as those derived from gelatin, casein, whey, corn zein, wheat gluten, and peanut proteins, exhibit strong oxygen and carbon dioxide barrier properties, particularly under low relative humidity ([Chen et al., 2019](#)). High-molecular-weight proteins, which are insoluble in water, are particularly effective for producing water-resistant films, making them highly suitable for bakery packaging. For example, gelatin-based coatings applied on substrates such as PE, PET, and PP have demonstrated significant improvements in oxygen and UV barrier properties. Similarly, zein-coated paper has outperformed polyethylene in terms of oxygen barrier capacity, making it a viable alternative to paraffin-coated paper for food packaging applications ([Coltelli et al., 2015](#)). The application of whey protein/pectin edible films prepared in the presence of transglutaminase (TGase) has proven effective in preventing moisture absorption in baked goods like taralli biscuits ([Rossi et al., 2014](#)). This coating acted as a water barrier, maintaining constant water content during prolonged storage and preserving the desired texture and crispness of the product. By preventing the transition from a glassy state to a rubbery state,

the coating effectively extended the shelf life of the biscuits and maintained their quality throughout storage.

Polysaccharides have also shown great promise in enhancing the barrier properties of packaging materials. Nanocellulose, in particular, has been extensively explored for developing coatings on both fossil-based and bio-based substrates ([Herrera et al., 2017](#)). Cross-linked nanocellulose coatings have demonstrated significant improvements in thermal stability, toughness, and barrier properties, including reductions in oxygen and water vapor permeability. In multilayer packaging systems, the incorporation of hydrophobic-modified nanocellulose fibers into a polylactic acid (PLA) matrix has shown considerable potential in providing sustainable and highly functional packaging solutions. These materials significantly reduce the water vapor transmission rate (WVTR) of paper, making them ideal for bakery products that require effective moisture control ([Song et al., 2014](#)). Materials such as chitosan and chitin, derived from natural sources like crustaceans, fungi, and insects, are well-known for their biocompatibility, biodegradability, and excellent gas and water vapor barrier properties. These materials, with their inherent film-forming ability and antimicrobial characteristics, are highly suitable for edible coatings and food packaging applications. Furthermore, they can be enzymatically modified to enhance their functionality, with derivatives such as quaternized and thiolated chitosan finding diverse applications in packaging, tissue engineering, and cosmetics ([Bahndral et al., 2024](#)). The use of sustainable biopolymer-based coatings in bakery packaging can significantly improve the barrier properties of paper-based packaging, reducing the environmental impact while ensuring product quality and consumer satisfaction ([Figure 11.2](#)).

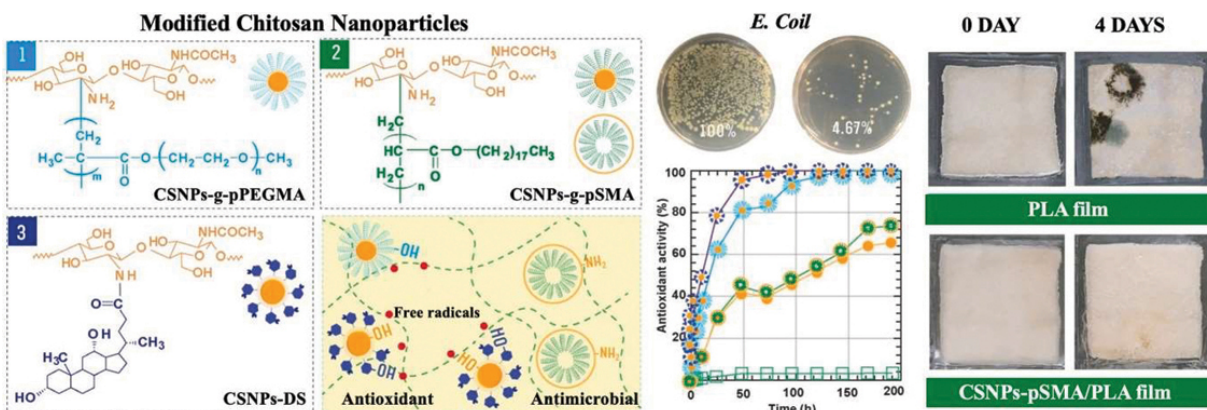


FIGURE 11.2 Active bioplastic packaging incorporating chitosan nanoparticles for bread preservation ([Kongkaoroptham et al., 2021](#)). [↗](#)

11.5.2 Mechanical Properties

The studies on packaging materials using biomaterials highlight the significant role of mechanical properties in enhancing the performance and sustainability of food packaging. For instance, chitosan-carboxymethyl cellulose films demonstrated improved elongation at break, indicating enhanced flexibility and tensile strength, which are essential for the material's durability in food applications such as preservative-free sliced wheat bread ([Noshirvani et al., 2017](#)). Similarly, chitosan-PLA films used for sliced bread packaging not only exhibited high antimicrobial activity but also maintained tensile strength and elongation properties, ensuring reliable performance during storage ([Kongkaoroptham et al., 2021](#)). The incorporation of ZnO nanoparticles into gelatin-polyethylene films and potato starch films significantly improved water vapor barrier properties, preventing the films from becoming brittle and ensuring mechanical stability under varying storage conditions ([Sahraee et al., 2020](#)). Furthermore, sulfur quantum dot-integrated alginate films exhibited a notable improvement in tensile strength and UV barrier properties, while maintaining stiffness and moisture control, showcasing the multifunctional nature of these materials in both mechanical and protective roles ([Riahi et al., 2022](#)). These studies emphasize the importance of optimizing mechanical properties like tensile strength, flexibility, and barrier

performance to enhance the functionality and sustainability of biomaterial-based packaging solutions. Chitosan films incorporated with apricot kernel essential oil exhibited enhanced tensile strength and reduced water vapor permeability (WVP), improving the structural integrity and moisture barrier properties of packaging for sliced bread ([Priyadarshi et al., 2018](#)). Similarly, cornstarch-chitosan films with sorbitol and grapefruit seed extract demonstrated high tensile strength and low solubility, which contributed to improved mechanical performance and extended bread shelf life by up to 20 days ([Jha, 2020b](#)). On the other hand, PLA/PBAT films containing thymol exhibited decreased glass transition temperature and melting temperature, which reduced tensile strength but improved elongation at break and thermal barrier properties, enhancing the flexibility and thermal stability of the packaging ([Suwanamornlert et al., 2020](#)). However, the incorporation of trans-cinnamaldehyde into PLA/PBAT films led to reduced barrier properties and mechanical strength due to the plasticizing effect and the formation of pores in the films, demonstrating how the choice and concentration of additives can influence the mechanical performance of the films ([Srisa & Harnkarnsujarit, 2020](#)). These studies highlight how various biopolymer films, when modified with active agents, can exhibit improved mechanical properties such as tensile strength, flexibility, and moisture barrier, which are crucial for effective food packaging.

11.5.3 Thermal Properties

Thermal stability is a crucial property of biopolymer-based packaging materials, determining their ability to withstand temperature variations and maintain structural integrity. The thermal behavior and stability of biopolymers can vary significantly depending on their specific type and source. Various analytical techniques, including Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), Dynamic Mechanical Analysis (DMA), and Thermomechanical Analysis (TMA), are commonly used to assess their thermal properties ([Singh et al., 2018](#); [Shah et al., 2024](#)). Key thermo-physical parameters, such as thermal conductivity,

diffusivity, glass transition temperature, crystallization temperature, melting point, and decomposition temperature, serve as critical metrics for evaluating the compatibility of biopolymers in food packaging applications. These parameters are particularly important when considering multi-polymer mixtures, as they provide insight into the uniformity and stability of polymer/biopolymer blends under fluctuating temperatures ([Naseri et al., 2020](#)).

Although starch-derived and other biopolymers exhibit improved mechanical strength and aesthetic attributes, they often lack the thermal insulation properties of synthetic plastics. Unlike conventional plastics, which restrict heat transfer due to their low thermal conductivity (0.15–0.4 W/mK), biopolymer-based packaging materials may require modifications to enhance thermal stability. The incorporation of bioactive compounds, the development of composite films using two or more biopolymers, or the addition of functional fillers can significantly influence key thermal characteristics, including thermal stability, melting temperature, and glass transition temperature, thereby improving the overall performance of biopolymer-based films for packaging applications ([Benbettaïeb et al., 2019](#)).

Recent studies have demonstrated that incorporating bioactive compounds and polymer blends can enhance the thermal stability of edible films used in bakery product packaging. For instance, the addition of carrageenan gum to pearl millet starch-based films increased their melting temperature (T_m) from 98°C to 118°C due to strong intermolecular interactions ([Sandhu et al., 2020](#)). Similarly, cassava starch-based films loaded with cinnamon essential oil exhibited improved thermal stability, attributed to enhanced compatibility between the polymer matrix and oil components ([Zhou et al., 2021](#)). The effect of essential oils on the thermal behavior of biopolymer films was further confirmed in carrageenan, guar gum, and glycerol-based edible films, where an increase in lemongrass essential oil concentration from 0.2% to 0.6% elevated the glass transition temperature (T_g) from 221.78°C to 241.26°C ([Rajeshwar & Anokhi, 2021](#)).

Crystallinity plays a vital role in determining the thermal resistance of packaging films. While edible films require a high degree of crystallinity for better thermal and mechanical performance, excessive crystallization can lead to increased brittleness, making industrial-scale applications challenging ([Shah et al., 2024](#)). Strategies such as co-crystallization or blending of biopolymers like collagen and alginic acid have been explored to enhance thermal stability while maintaining mechanical flexibility, achieving an increase in thermal resistance by 15°C ([Mitra et al., 2011](#)). Additionally, the incorporation of nanomaterials such as cellulose nanocrystals and starch nanocrystals into edible films has been reported to improve both crystallinity and heat resistance, as seen in gelatin-based films reinforced with bacterial cellulose nanocrystals ([George, 2012](#)).

Crosslinking approaches have also been widely employed to improve the thermal properties of biopolymer-based bakery packaging. The addition of natural crosslinkers like tannic acid, citric acid, and xylose has been shown to enhance the stability of gelatin, casein, and polysaccharide-based films ([Shah et al., 2024](#)). Furthermore, thermal treatment combined with irradiation has been found to improve film network density and thermal stability, as demonstrated in gelatin-nutshell fiber composites, where exposure to a 40 kGy electron beam significantly increased thermal resistance ([Inamura et al., 2010](#)). Given the relatively low thermal conductivity of biopolymers compared to synthetic plastics (0.15–0.4 W/mK), innovative strategies such as polymer blending, nano-reinforcement, and crosslinking modifications are essential for optimizing their application in bakery product packaging ([Shah et al., 2024](#)). These approaches help mitigate heat sensitivity, prevent degradation under high-temperature storage conditions, and enhance the barrier properties necessary for prolonging the shelf life of bakery products.

11.5.4 Structural and Morphological Properties

The structural and morphological properties of biopolymer-based packaging significantly impact film formation, integrity, and performance. These

properties include surface roughness, porosity, homogeneity, and polymer interactions, all of which influence barrier properties, adhesion, and stability. The microstructure of these films can be analyzed using techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray diffraction (XRD) ([Wu et al., 2016](#)). A well-structured film ensures effective packaging functionality, preventing excessive moisture absorption, oxygen permeability, and microbial contamination.

The rheological behavior of film-forming solutions (FFS) plays a crucial role in determining the final film's structural and morphological characteristics. The viscosity of FFS directly affects film uniformity, thickness, and surface properties. High-viscosity solutions often result in thicker films with uneven surfaces, while low-viscosity solutions may lead to poor polymer interactions, compromising mechanical integrity ([Bai et al., 2015](#); [Silva-Weiss et al., 2014](#)). Proper control over the capillary leveling of FFS is necessary to avoid gravity-induced sagging and ensure a smooth, homogeneous surface ([Maloy et al., 2012](#)). Modifications in the polymer chain through grafting reactions can also influence the structural properties of the film. The introduction of gallic acid into chitosan chains via a free radical grafting reaction led to more elastic networks at lower gallic acid values but resulted in reduced mechanical strength and water resistance in the final film ([Wu et al., 2016](#)). Such modifications highlight how small changes in molecular structure can significantly alter film microstructure and functionality. Surface morphology plays a key role in determining barrier efficiency, as compact, uniform films provide better resistance to moisture and gas diffusion. Hydrophilicity and hydrophobicity, which are crucial in defining water uptake and surface adhesion, can be assessed using contact angle measurements ([Xiao et al., 2012](#)). Hydrophilic surfaces, such as those found in starch-based films, tend to absorb moisture, which can affect packaging durability in high-humidity environments. In contrast, surface modifications through the incorporation of lipid components or nanofillers can improve hydrophobicity and create smoother, less porous films ([Maloy et al., 2012](#)).

Protein-based films exhibit structural characteristics that depend on their molecular properties, such as intermolecular hydrogen bonding, electrostatic interactions, and covalent crosslinking ([Silva-Weiss et al., 2014](#)). The ability of proteins to form strong, viscoelastic matrices makes them suitable for biopolymer-based packaging. However, variations in molecular weight, charge distribution, and polymer conformation lead to differences in film microstructure. Collagen and gelatin films, for example, exhibit good mechanical properties and oxygen barrier capacity but are highly sensitive to humidity, which limits their application ([Mujtaba et al., 2022](#)). Whey protein and casein-based films produce water-insoluble coatings that provide effective oxygen permeability control, making them suitable for food packaging ([Coltelli et al., 2015](#)). Zein-based films, derived from corn, are known for their high strength, smooth surfaces, and glossiness, but their inherent brittleness requires plasticization to improve flexibility ([Benbettaieb et al., 2019](#)).

Crosslinking is an essential modification strategy to enhance film density and improve mechanical stability. Heat treatment, enzymatic modification, and the addition of crosslinkers have been used to create denser polymer networks with better film compactness and surface integrity ([Shah et al., 2024](#)). The incorporation of gallic acid into chitosan films altered polymer entanglement, increasing antimicrobial efficacy but reducing mechanical flexibility ([Wu et al., 2016](#)). Plasticization is another key factor in defining morphological properties, as plasticizers such as glycerol and sorbitol can enhance film flexibility. However, excess plasticizer may cause phase separation, leading to reduced surface compactness and weakened structural integrity ([Silva-Weiss et al., 2014](#)). The interaction between proteins and polysaccharides also plays a role in film morphology, as blending these biopolymers results in composite films with enhanced mechanical durability and smoother surfaces ([Mujtaba et al., 2022](#)).

The development of composite films by blending proteins, polysaccharides, and other biopolymers has been widely explored to optimize structural and morphological properties. Combining biopolymers with reinforcing agents such as cellulose nanocrystals or montmorillonite

clay results in films with improved compactness, reduced porosity, and enhanced surface properties. Zein-based films reinforced with nanocellulose exhibit high-gloss surfaces and increased density, improving barrier performance while requiring plasticization to maintain flexibility ([Benbettaieb et al., 2019](#)). Similarly, chitosan-based films with gallic acid grafting have demonstrated increased crosslinking and improved microstructure, affecting elasticity and surface properties while enhancing antimicrobial functionality ([Wu et al., 2016](#)). Blending gelatin with soy protein has been shown to enhance film flexibility and mechanical strength due to the complementary structural properties of linear and globular protein matrices ([Mujtaba et al., 2022](#)). The structural and morphological properties of biopolymer-based films are critical in determining their suitability for bakery product packaging. Factors such as rheology, polymer interactions, film microstructure, and surface modifications directly impact film formation, adhesion, and long-term stability. Advances in composite films, nano-reinforcement, and crosslinking techniques continue to improve biopolymer-based packaging, making it a viable alternative to synthetic plastics while maintaining product integrity and extending shelf life.

11.5.5 Antimicrobial Properties

Antimicrobial properties in packaging materials play a crucial role in preserving the shelf life and safety of bakery products by preventing microbial spoilage. Various approaches have been explored to incorporate antimicrobial agents into food packaging, including both edible coatings and non-edible active packaging solutions. These antimicrobial strategies help reduce the growth of harmful microorganisms, such as molds, yeasts, and bacteria, which can cause food spoilage and deterioration.

Biopolymer-based edible coatings have emerged as an innovative, sustainable solution to enhance the quality and shelf life of bakery products. These coatings, often composed of polysaccharides, proteins, lipids, or combinations of these materials, form thin protective layers that reduce moisture loss, prevent microbial spoilage, and extend freshness. One of the

key benefits of these coatings is their ability to incorporate natural antimicrobial agents, such as organic acids, plant extracts, and probiotic bacteria. For instance, lactic acid bacteria, including *Lactobacillus plantarum*, are known to produce antifungal substances during sourdough fermentation, effectively retarding mold growth and extending bread shelf life. In addition to their antifungal effects, probiotic bacteria such as *Lactobacillus acidophilus*, *Bifidobacterium bifidum*, and *Lactobacillus casei* have been successfully incorporated into edible coatings, enhancing food properties by promoting gut health and improving immunity, alongside improving food safety and preserving product quality ([Guimaraes et al., 2018](#); [Gregirchak et al., 2020](#)).

Active edible coatings have demonstrated the ability to significantly reduce microbial contamination in bakery products. For instance, coatings infused with essential oils such as cinnamon or oregano have shown strong antifungal effects. In a study, *Rhizopus stolonifer* growth was inhibited in sliced bread using paper packaging with 6% cinnamon essential oil, which migrated through the headspace to prevent fungal growth ([Rodriguez et al., 2008](#)). Similarly, gliadin-based films containing 3–5% cinnamaldehyde have proven effective in suppressing the growth of *Penicillium expansum* and *Aspergillus niger* in bakery products. These films not only prolonged shelf life but also maintained bread freshness for up to 27 days compared to just four days in control samples ([Balaguer et al., 2013](#)).

In addition to edible coatings, non-edible active packaging materials have also gained significant attention in extending the shelf life of bakery products. These materials contain antimicrobial agents that actively prevent microbial growth by releasing active compounds into the surrounding environment. For example, films made from chitosan, a natural polymer with inherent antimicrobial and antifungal properties, have been incorporated with other bioactive substances like propionic acid to form active packaging materials that preserve food quality. Moreover, innovative modifications of chitosan, such as its combination with polyethylene glycol methyl ether methacrylate (PEGMA) or zinc oxide nanoparticles (ZnO NPs), have enhanced both the mechanical and antimicrobial properties of

packaging materials. Studies have demonstrated that chitosan films combined with ZnO NPs can significantly extend the shelf life of sliced wheat bread, increasing its microbial and staling shelf life from 3 days to 35 days ([Bouzidi et al., 2024](#)).

Furthermore, biocomposites that combine biopolymers like chitosan or polylactic acid (PLA) with natural fibers such as cellulose or hemp are being explored for active antimicrobial packaging. These biocomposites benefit from the strength and flexibility provided by the fibers, while the biopolymer matrix offers antimicrobial properties. By integrating antimicrobial agents such as essential oils, silver nanoparticles, or plant extracts into these biocomposite materials, packaging can prevent microbial growth while maintaining sustainability and biodegradability. Studies evaluating bioplastic materials like Bio-PE, PLA, and PBSA have shown that active packaging can preserve bakery product quality by controlling moisture and preventing microbial growth. For example, bio-PE, a bio-based material, was found to maintain quality parameters such as weight loss, crust and crumb hardness, and springiness in hotdog and hamburger buns at levels similar to conventional polyethylene packaging. However, other materials like Biodolomer® showed higher weight loss and drier edges due to a higher water vapor transmission rate (WVTR), which affected the overall product quality ([Putranda, 2017](#)).

In addition, innovative approaches are being explored, such as thermoplasticized food waste films. For example, bread waste has been thermoplasticized with glycerol and blended with poly(butylene adipate-co-terephthalate) (PBAT) to create films with strong mechanical, thermal, and moisture-resistant properties. These films have shown the potential for use in food packaging, demonstrating that food waste can be repurposed into functional bioplastics, which significantly contributes to reducing environmental waste and supporting sustainability ([Bouzidi et al., 2024](#)). By integrating antimicrobial agents into both edible coatings and non-edible active packaging, bakeries can not only enhance the safety and shelf life of their products but also align with consumer demand for clean-label, sustainable, and functional packaging solutions. This approach represents a

convergence of sustainability, functionality, and food safety in modern food packaging.

11.5.6 Controlled Release Mechanisms

The food packaging industry is transitioning toward active packaging solutions that are both environmentally friendly and capable of preserving food quality and extending shelf life. Among these innovations, absorbent pads play a crucial role in reducing excess liquid exuded by fresh products, thereby enhancing their shelf life. Aerogels, with their lightweight and porous structure, are ideal for such applications, particularly when made using bio-based and biodegradable polymers like starch, cellulose, and their derivatives. The incorporation of cross-linkers and advanced drying techniques, such as freeze-drying or supercritical CO₂ drying, ensures the development of high-performance aerogels with optimal porosity and absorption capacity. By utilizing renewable resources and minimizing reliance on petroleum-derived materials, aerogel-based absorbent pads represent a sustainable and efficient solution for modern food packaging needs ([Gupta et al., 2023](#)). A study developed controlled-release packaging for folic acid using a spray-drying process with various biopolymers as encapsulating agents. Microparticles exhibited 100% encapsulation efficiency, except for those with modified starch, and yields ranged from 13% to 50%. The microparticles showed diverse morphologies (smooth, rough, regular, or irregular) depending on the biopolymer used, though folic acid incorporation did not affect their shape. Release profiles varied based on the encapsulating agent, achieving complete release in under 2 hours, and mathematical modeling (Weibull model) effectively predicted the release behavior. For slower release, pectin or sodium alginate were more suitable, while modified starch, modified chitosan, and arabic gum enabled faster release, making them ideal for applications requiring immediate bioactive availability. The system demonstrated potential for encapsulation and protection of photosensitive bioactives during processing and storage stages, offering oxidation and light protection. These microparticles are

promising for food, pharmaceutical, and cosmetic applications, with adaptable release profiles tailored for efficient absorption or instantaneous bioavailability based on the intended use ([Estevinho et al., 2020](#)).

Another study developed a controlled-release antimicrobial sachet for white bread shelf-life extension using EVOH-coated paper and a PBS/geraniol blend. Optimized with 10 wt% geraniol for antimicrobial activity, the sachet effectively inhibited gram-positive and gram-negative bacteria. A three-layer EVOH coating (~450 μm) provided optimal water vapor barrier properties and controlled geraniol release, which increased with relative humidity. Shelf-life tests showed the sachet delayed bread spoilage by over three weeks while preserving textural quality ([Petchwattana et al., 2021](#)). Cashew gum-gelatin (CG-G) films with ferulic acid (FA) as a cross-linking agent and *Cymbopogon citratus* essential oil (EO) were developed for bread packaging. FA effectively cross-linked the CG-G matrix, reducing solubility and maintaining low opacity and water vapor permeability (WVP). Infrared (IR) analysis confirmed cross-linking, leading to compact films with enhanced elongation-at-break (up to 140%) and reduced tensile strength by 38%, imparting plastic-like properties. The EO improved mechanical performance and exhibited antimicrobial action, preserving bread for six days compared to three days with polyethylene packaging ([Oliveira et al., 2020](#)).

11.5.7 Biodegradation

Biodegradable packaging materials are increasingly vital in the bakery industry as companies respond to consumer demands for sustainable practices. Derived from natural sources such as plant-based polymers, paper, and cardboard, these materials offer significant environmental benefits over traditional plastics. One of their primary advantages is the ability to decompose naturally, reducing landfill waste and minimizing pollution. For instance, paperboard boxes are gaining traction for pastries and cakes due to their biodegradability, while films made from renewable resources present a promising alternative for bread packaging. The shift

toward such materials aligns with the bakery industry's broader sustainability goals, including reducing carbon footprints and enhancing brand image. Functional coatings like beeswax-chitosan emulsions applied to paper-based packaging have been shown to enhance the shelf life and microbiological stability of bakery products. Studies demonstrated that such coatings improved the sensory and analytical attributes of bread while providing an environmentally friendly alternative to non-biodegradable plastics like LDPE and PP. Additionally, consumer studies validated a preference for coated paper packaging due to its green functionality and reduced environmental impact ([Bhardwaj et al., 2022](#)).

11.6 CHALLENGES IN INCORPORATING BIOMATERIALS IN BAKERY PRODUCTS

As consumers increasingly prioritize sustainable and eco-friendly packaging solutions, the demand for environmentally friendly options in bakery products has surged. This shift is driven by growing environmental concerns and a preference for healthier, minimally processed foods. Active and intelligent packaging technologies, especially those utilizing biodegradable materials and functional additives, are emerging as promising innovations. These technologies not only extend shelf life and preserve quality but also help reduce food waste, aligning with consumer preferences for both convenience and sustainability. For example, incorporating biomaterials like chitosan-based nanoparticles or natural antioxidants can enhance packaging performance by providing antimicrobial and antioxidant properties, thereby maintaining product freshness.

However, the widespread adoption of these packaging technologies is heavily influenced by consumer perceptions and trust. While there is significant enthusiasm for eco-friendly solutions, skepticism remains regarding the safety of novel approaches, such as nanotechnology or the use

of active agents in packaging. To gain consumer confidence, it is essential to ensure transparency in communicating the safety and benefits of these technologies, supported by regulatory assurance and eco-labeling. Additionally, consumers tend to favor packaging that provides clear information about food quality, such as indicators of freshness or leakage, further emphasizing the importance of intelligent packaging systems.

Moreover, certain limitations of edible coatings must be considered. These coatings are often hydrophilic, which can compromise their moisture barrier capabilities, and they may struggle to adhere properly to hydrophobic surfaces. Chemical modifications to improve hydrophobicity can mitigate these issues but may introduce additional costs and regulatory challenges. Furthermore, securing safety approvals, such as GRAS (Generally Recognized as Safe) certification, is essential for ensuring the safety of these materials in commercial applications ([Asfaq et al., 2023](#)).

For the broader acceptance of sustainable biomaterials in bakery packaging, the industry must focus on raising awareness about their environmental and functional benefits while addressing misconceptions and ensuring affordability. By integrating innovative solutions with effective communication strategies, these technologies can meet consumer expectations and contribute to a more sustainable future ([Aday & Yener, 2015](#)).

11.7 ENVIRONMENTAL IMPACT AND SUSTAINABILITY ASSESSMENT

The environmental impact of biomaterials used in bakery packaging is a crucial consideration in their development and application, with biodegradability being a key factor in reducing long-term waste. Biomaterials such as potato starch-based trays, starch laminates, silvergrass, and coconut fiber trays exhibit varying rates of degradation based on their composition. For example, materials derived from natural starch, such as

potato starch-based trays, degrade rapidly, making them suitable for short-term applications where biodegradability is essential. Similarly, materials like silvergrass and coconut fiber trays also show fast degradation rates, offering a sustainable option for packaging that aligns with environmental goals. On the other hand, other materials, such as paper-based packaging and recycled paper pulp trays, provide a balance between performance and environmental impact, degrading at a medium rate ([Song et al., 2009](#)).

In contrast, experimental materials like PLA (polylactic acid), starch/PCL (polycaprolactone) blends, and polypropylene (PP) with biodegradable additives degrade more slowly, which may limit their environmental benefits in the short term despite offering durable packaging solutions. The slower degradation rates of these materials suggest that they are more suited for long-term packaging applications where durability and strength are required. However, the incorporation of bio-additives and starch into these materials further delays their breakdown, illustrating the trade-off between material longevity and environmental sustainability. While biopolymers provide a promising alternative to traditional plastics, challenges such as potential environmental pollution during disposal and the release of methane from landfilling or anaerobic digestion highlight the need for a comprehensive approach to the entire life cycle of these materials ([Cruz et al., 2022](#)).

Therefore, while biomaterials like starch-based trays and bioplastics offer clear advantages in terms of biodegradability, their environmental impacts during the disposal phase must be carefully managed. To ensure the sustainability of bakery packaging, the integration of these materials into efficient disposal systems such as composting, recycling, or waste-to-energy technologies is essential. The development of biodegradable materials for bakery packaging offers a viable solution to reducing plastic waste, but it requires a balanced consideration of their environmental impact throughout their lifecycle.

11.8 APPLICATIONS

Biopolymer-based packaging is widely applied in bakery product packaging due to its ability to enhance food preservation, extend shelf life, and reduce microbial spoilage while offering a sustainable alternative to synthetic plastics. These materials are used in various forms, including edible coatings, active biopolymer films, and controlled-release antimicrobial packaging, tailored to meet the specific preservation needs of different bakery goods. Edible coatings have been effectively used for bread, biscuits, muffins, and cakes, where they act as a protective layer to reduce moisture loss and inhibit microbial growth. For instance, a probiotic starch-based coating incorporating *Lactobacillus acidophilus* successfully maintained the sensory quality of baked bread while preventing microbial contamination ([Altamirano-Fortoul et al., 2012](#)). Similarly, okra mucilage coatings on biscuits improved moisture barrier properties, preventing crispness loss and microbial spoilage ([Senanayake et al., 2021](#)), while a triticale flour-based coating delayed crumb firming in muffins, reducing weight loss during storage ([Bartolozzo et al., 2016](#)).

Active biopolymer films have also been explored for sliced bread, sponge cakes, and panettone, integrating bioactive agents such as essential oils, nanoparticles, and antimicrobial compounds. A composite chitosan-carboxymethyl cellulose film with oleic acid and ZnO nanoparticles significantly extended the microbial shelf life of sliced wheat bread from 3 to 35 days by reducing fungal growth and improving water vapor barrier properties ([Noshirvani et al., 2017](#)). Similarly, gelatin nanocomposite films containing ZnO nanoparticles preserved the chemical and sensory quality of sponge cakes by preventing fungal contamination and oxidation ([Sahraee et al., 2020](#)). Starch-based edible films have also shown effectiveness in increasing the shelf life of mini panettone by 130%, reducing storage-related product loss ([Saraiva et al., 2016](#)).

Controlled-release antimicrobial packaging is another innovative application, particularly for bread storage. A PBS/geraniol blend sachet with

an EVOH-coated paper layer was developed to release antimicrobial agents gradually, successfully delaying bread spoilage for over three weeks while maintaining textural quality ([Petchwattana et al., 2021](#)). Additionally, cashew gum-gelatin films infused with *Cymbopogon citratus* essential oil extended the shelf life of bread from three to six days, outperforming traditional polyethylene packaging in microbial protection ([Oliveira et al., 2020](#)). The integration of biopolymer-based packaging materials into bakery applications not only helps in extending product shelf life but also meets the growing demand for sustainable packaging alternatives in the food industry. By replacing traditional plastic-based wrappers with biodegradable, functional packaging solutions, bakeries can enhance food safety, reduce environmental impact, and minimize food waste, making biopolymers a promising innovation in the future of bakery product packaging.

11.9 FUTURE PROSPECTS AND INNOVATIONS

The future of biomaterials in bakery packaging is marked by innovations aimed at addressing sustainability challenges while enhancing functionality. With increasing consumer demand for environmentally friendly packaging, the development of biodegradable and compostable materials is expected to gain momentum. Advances in bio-based polymers, such as polylactic acid (PLA) and starch-based materials, offer promising alternatives to conventional plastics by providing effective barrier properties and reducing environmental impact. These materials are increasingly being integrated with intelligent packaging systems that can monitor freshness, enhance product safety, and improve consumer engagement.

Emerging technologies, including the incorporation of active agents like natural antioxidants and antimicrobial compounds, hold the potential to extend the shelf life of bakery products while maintaining their quality.

Future developments are also likely to focus on addressing current limitations, such as the hydrophilic nature of some biomaterials and their reduced durability compared to synthetic polymers. Innovations in material modification, such as blending or chemical treatments, could overcome these challenges and create hybrid solutions that balance biodegradability with performance.

Additionally, the adoption of biomaterials is expected to be supported by advancements in disposal infrastructure, including industrial composting and recycling facilities, to ensure efficient end-of-life management. As regulatory frameworks and eco-certifications evolve to support sustainable packaging, biomaterials will play a crucial role in reducing the carbon footprint of bakery packaging while meeting consumer expectations for sustainability and functionality.

11.10 CONCLUSION

In conclusion, the use of biomaterials for packaging bakery products represents a promising and sustainable shift in the food packaging industry. As consumer demand for eco-friendly solutions increases, biomaterials such as starch-based polymers, PLA, chitosan, and natural fibers offer significant advantages over traditional plastic packaging. These materials, derived from renewable sources, provide biodegradable and compostable alternatives, contributing to reduced environmental impact. The incorporation of biomaterials enhances the barrier properties of packaging, protecting bakery products from moisture, oxygen, and other contaminants, thus extending shelf life and preserving product quality.

However, the adoption of biomaterials in bakery product packaging faces several challenges. These include the optimization of mechanical properties, the need for effective moisture and grease resistance, and overcoming consumer skepticism regarding novel technologies such as active and intelligent packaging. While certain edible coatings and active packaging

solutions show great potential in enhancing food preservation, their cost, regulatory approval processes, and scalability remain significant hurdles. Additionally, ensuring that these materials meet the durability and performance standards required for food packaging is critical for their widespread adoption. Despite these challenges, the ongoing research and development of biopolymer-based materials offer a pathway to more sustainable packaging solutions for bakery products. By addressing these limitations, optimizing material properties, and promoting consumer education on the safety and benefits of these technologies, the packaging industry can move toward more environmentally friendly and functional solutions. Ultimately, the future of bakery product packaging lies in the successful integration of innovative biomaterials that balance sustainability, performance, and cost-effectiveness, aligning with both environmental goals and consumer expectations.

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Consumer Perception and Acceptability of Sustainable Packaging Systems

12

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12.1 CURRENT STATE OF SUSTAINABLE PACKAGING

In 2015, the United Nations member states approved the 2030 Agenda for Sustainable Development. The agenda includes the 17 Sustainable Development Goals to improve health and education, reduce inequality, spur economic growth, tackle climate change, and work to preserve our oceans and forests ([United Nations, 2015a](#)). The objective of this agenda is to protect the planet from environmental harm for the present and future generations through different measures, including taking an urgent action on climate change, sustainable consumption and production, and sustainable natural resources management ([United Nations, 2015b](#)). Since the United Nations passed its 2030 Agenda for Sustainable Development, more global organizations have developed initiatives to align with the United Nations Agenda. For example, the Ellen McArthur Foundation's

sustainability initiatives are aligned with this agenda, and their main objective is to promote a circular economy, a system where materials never become waste and natural resources are regenerated. In a circular economy, products and materials are kept in a circular system by different processes, including maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy strategy not only addresses climate change but other global challenges such as biodiversity loss, waste, and pollution. According to the Ellen McArthur [Foundation \(2024\)](#), the circular economy is based on three design principles: eliminate waste and pollution; circulate products and materials (at their highest value); and regenerate nature.

In the United States, the Sustainable Packaging Coalition (SPC) is a well-known organization that promotes sustainability initiatives aligned with the United Nations Agenda. This organization promotes the power of the entire packaging value chain industry to advance sustainable packaging, through education, collaboration, and action ([The Sustainable Packaging Coalition, 2024](#)). These sustainability initiatives from the United Nations and other global and local organizations are now supported by regulations. Therefore, the sustainable packaging initiatives are gaining momentum as these regulations are passed. One of the most common regulations is the Extended Producer Responsibility (EPR), which is a type of policy approach that assigns producers responsibility for the end-of-life of their products. These policies are being passed globally fast enough that global CPG companies are putting these regulations as business priorities by engaging with regulators and business partners (e.g., suppliers, consultants, researchers in academia), developing strategies, and making changes to their current products. These regulations include both financial responsibility and operational responsibility. The fee amount and type differ depending on the regulation. Moreover, producers are required to provide funding and/or services that assist in managing covered products after the use phase. For example, a CPG company must provide funding to open a new Materials Recovery Facility (MRF) in the country where they sell their products ([The Sustainable Packaging Coalition, 2021](#)). Most EPR programs

encourage or require producers of packaging products to join a collective producer responsibility organization (PRO), though many allow producers to comply individually. The PRO then develops a producer responsibility plan and manages the producer responsibility program, which is typically required to be a nonprofit organization, and a common approach is to allow for multiple PROs to operate within a single region's EPR program. Some regulations refer to a PRO as a stewardship organization and stewardship plan. As mentioned before, these regulations have a financial responsibility that may vary between EPR regulations, but in most EPR programs, producers pay fees to the PRO. The PRO then distributes the funds to cover the costs required by program legislation. These costs provide funding for the end-of-life management of the covered products, such as collection, sortation, and processing. The covered products are the specific products or materials that must be managed within the EPR program and are defined in the EPR regulation or in the producer responsibility plan ([The Sustainable Packaging Coalition, 2021](#)).

Moreover, new regulations extend cost coverage from producers (e.g., CPG companies) to include outreach and education, infrastructure improvements, and end-market development for recycled materials. Organizations and policymakers are increasingly pointing to effective EPR as a necessary component of a comprehensive approach to addressing recycling challenges and concerns over single-use product pollution ([The Sustainable Packaging Coalition, 2021](#)).

EPR regulations are changing the perceptions and acceptability of sustainable packaging among consumers. In fact, regulations and consumers are the two key drivers of the increased use of sustainable packaging and incorporation of new strategies for sustainable packaging. Companies such as CPG companies are driven to promote sustainable packaging not only by new regulations, laws, taxation, and other actions promoted by governments to make packaging sustainable and reduce the environmental impact but also by the increasing importance from consumers to reduce the environmental impact ([Wandosell et al., 2021](#); [Nguyen et al., 2020](#)). CPG companies have responded to an increased

demand from consumers for sustainability initiatives and increased use of sustainable packaging based on the realization of a needed shared value. In the United States, a well-known organization in sustainable packaging and sustainability initiatives, the Sustainable Packaging Coalition (SPC) developed a database about packaging sustainability goals and metrics from many companies ([The Sustainable Packaging Coalition, 2022](#)). For example, various CPG companies set targets in action plans for improving the sustainability of their packaging by 2025 and 2030. These targets will be achieved by many different actions, including design and selection of packaging components and materials and value chain modifications that will require significant investment of resources and capital with the expectation of increasing market shares and consumer acceptability and satisfaction ([Boz et al., 2020](#)).

For a successful integration of sustainability initiatives into the design, development, and commercialization processes, management commitment is essential, meaning the senior leaders from CPG companies such as the chief executive officer (CEO), chief financial officer (CFO), vice presidents (VPs), and directors should believe, support, and encourage teams to implement sustainability initiatives ([Hallstedt et al., 2013](#); [Jansson et al., 2017](#); [Johansson, 2020](#)). Some of the deciding factors used to implement these sustainability strategies and sustainable packaging include:

- Understanding trade-offs between sustainable materials and current materials,
- Analyzing options for trade-offs,
- Evaluating packaging requirements and sustainability considerations,
- Integrating end-of-life scenarios and a circular economy process ([De Koeijer, De Lange & Wever, 2017](#)).

Moreover, the packaging designers, engineers, and scientists should involve corporate responsibility, marketing, and legal departments during the packaging development pipeline, including the early stages. These critical internal stakeholders must assist in incorporating the sustainability strategy

and goals into development teams' decision-making processes. Packaging designers, engineers, and scientists need to design and develop new sustainable packaging for current and new products based on a comprehensive and holistic analysis of all implications of the packaging life cycle ([Pålsson & Hellström, 2016](#)). These implications include cost-effectiveness, consumer insights, analysis of chemical and physical properties of the product and packaging, migration of volatile compounds between the packaging and product, shelf life studies, supply chain demands, manufacturing capabilities, and business needs. As mentioned previously, CPG companies must develop a package that is cost-effective due to a low profit margin compared with other industries, such as pharmaceutical and medical industries. Also, most of these CPG companies are now under regulations, laws, taxation, and other actions promoted by local and global governments to make packaging sustainable and reduce the environmental impact. However, the supply of sustainable packaging components and materials can be short. Therefore, the sustainable packaging industry needs to address the following challenges in order for companies to address their 2025 and 2030 sustainability goals:

- Improve supply chain efficiency encompassing industrial packaging
- Minimize environmental impact of industrial packaging
- Enhance industrial packaging development process
- Tackle implications of industrial packaging regulatory compliance ([Silva & Pålsson, 2022](#))

As mentioned before, consumers and EPR regulations have driven sustainability as one of the integral functions of packaging along with protecting the product, ensuring food quality and safety, facilitating transportation and logistics, and communicating with consumers ([Boz et al., 2020](#)). Despite the recent efforts for sustainable packaging, there are opportunities for improvement, such as increasing supply chain and security, improving cost-effectiveness and barriers (e.g., water, oxygen, etc.), expanding the use of life cycle assessment (LCA) for sustainable

packaging, and finding ways to include sustainable packaging within a circular economy. Even with these challenges, sustainable packaging is growing and evolving quickly, so CPG companies need to stay informed about new sustainable materials and technologies. In the following section, sustainable packaging practices will be examined, and various types and their applications will be explored.

12.2 SUSTAINABLE PACKAGING

Sustainability, as a guiding principle, has deep historical roots. Its applications in food packaging date back to early civilizations, where the preservation of food was crucial for survival between harvest seasons ([Boz et al., 2020](#)). The modern understanding of sustainability was formally articulated in the 1987 Brundtland Report by the United Nations, which defined sustainable development as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” ([Boz et al., 2020](#); [World Commission on Environment and Development, 1987](#)). Corporations, organizations, NGOs, and policymakers have formalized this foundational definition and adapted it across various sectors, leading to over 300 definitions of “sustainability” today ([Boz et al., 2020](#); [Geissdoerfer et al., 2017](#)). For example, companies like Coca-Cola, McDonald’s, and Tesco all have their own unique definitions for sustainability and sustainable packaging, contributing to consumer confusion about what constitutes sustainable packaging ([Boz et al., 2020](#); [Jerzyk, 2016](#)). Although the definition of sustainable packaging remains a topic of ongoing debate, companies are increasingly seeking actionable strategies to integrate sustainable development principles into the design and production of product packaging ([Sonneveld et al., 2005](#)). It is therefore vital in the realm of packaging to establish a universally accepted definition of sustainable packaging. Out of the many definitions of sustainability, just two specifically address packaging: the Sustainable

Packaging Alliance (SPA) definition and the Sustainable Packaging Coalition (SPC) definition ([Boz et al., 2020](#)).

The Sustainable Packaging Alliance (SPA) developed a definition that incorporates four levels of consideration. A key outcome of this initiative was a comprehensive definition of sustainable packaging that acknowledges its role within broader social and economic systems ([Sonneveld et al., 2005](#)). This definition incorporates four levels (Society, Packaging System, Packaging Material, and Packaging Component) and four principles (Effective, Efficient, Cyclic, and Safe) of consideration. According to SPA's definition, "packaging will support sustainable development if [those] principles are met" ([Sonneveld et al., 2005](#)).

This approach distinguishes between different levels of impact in packaging design at the macro level (Society), which relates to societal prosperity and well-being; at the functional performance level (Packaging System), concerning the product and packaging system's efficiency and effectiveness; at the environmental performance level (Packaging Material), focusing on material impact and waste prevention; and at the micro level (Packaging Component), addressing human and eco-toxicity of packaging components ([James et al., 2005](#); [Sonneveld et al., 2005](#)). This can be seen in [Figure 12.1](#).

[Sonneveld et al. \(2005\)](#) summarize this first, preliminary definition and provide further definitions for what is meant by each principle in [Table 12.1](#). The "Effective" principle, which is applied at the "Society" level, is met when the packaging "adds real value to society by effectively containing and protecting products as they move through the supply chain and by supporting informed and responsible consumption." The "Efficient" principle, which is applied at the "Packaging System" level, is met when "packaging systems are designed to use materials and energy as efficiently as possible throughout the product life cycle. This should include material and energy efficiency in interactions with associated support systems such as storage, transport and handling." The "Cyclic" principle, which is applied at the "Packaging Material" level, is met when "packaging materials are cycled continuously through natural or (industrial) technical

systems, minimizing material degradation and/or the use of upgrading additives.” The “Safe” principle, which is applied at the “Packaging Component” level, is met when “packaging components do not pose any risks to human health or ecosystems. When in doubt the precautionary principle applies” ([James et al., 2005](#); [Sonneveld et al., 2005](#)).

The Sustainable Packaging Coalition (SPC) offers another widely accepted definition, which relates to the use of renewable energy for producing more sustainable packaging. Specifically, it states that such packaging should be produced using renewable energy sources like biomass, geothermal, and hydroelectric sources, as well as wind power. Additionally, the SPC acknowledges the challenges of completely shifting from fossil-based energy and materials to renewable alternatives. One such challenge is that, according to the definitions, compostable packaging cannot be considered sustainable if it has not been made using the appropriate energy optimization and materials and if it does not satisfy profitability and the market criteria. Promoting it as sustainable packaging would therefore be misleading ([Boz et al., 2020](#)).

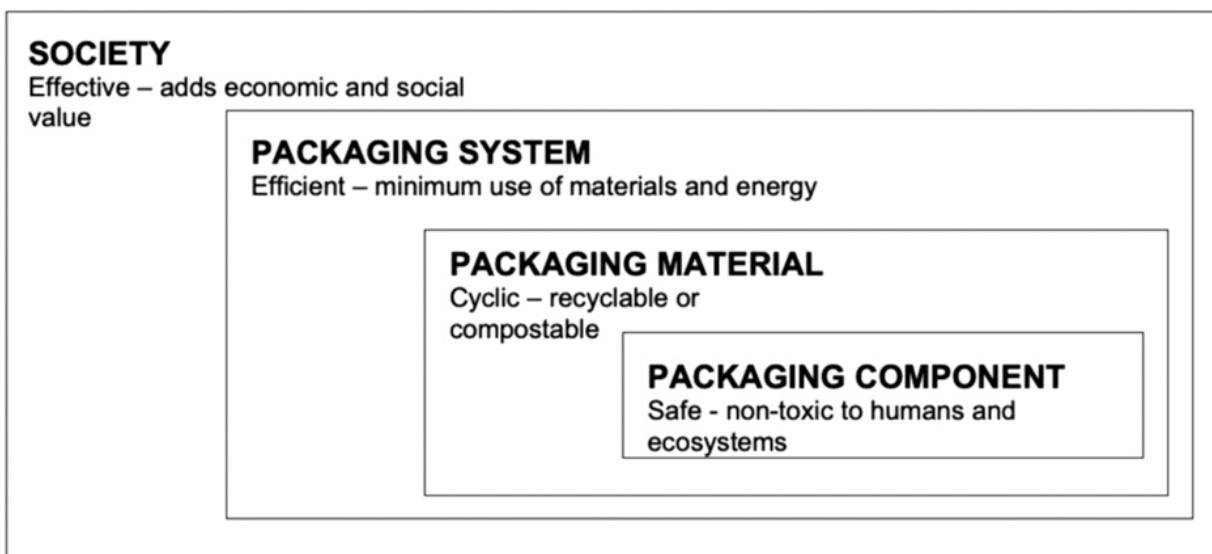


FIGURE 12.1 The four levels and principles of Sustainable Packaging Alliance’s sustainable packaging definition. Source: [James et al., 2005](#). [↗](#)

TABLE 12.1 SPA's Sustainable Packaging Definition ([James et al., 2005](#); [Sonneveld et al., 2005](#)) 

<i>PACKAGING WILL SUPPORT SUSTAINABLE DEVELOPMENT IF THE FOLLOWING PRINCIPLES ARE MET.</i>		
<i>PRINCIPLE</i>		<i>LEVELS AT WHICH THE PRINCIPLE IS APPLIED</i>
Effective	It adds real value to society by effectively containing and protecting products as they move through the supply chain and by supporting informed and responsible consumption.	Society
Efficient	Packaging systems are designed to use materials and energy as efficiently as possible throughout the product life cycle. This should include material and energy efficiency in interactions with associated support systems such as storage, transport, and handling.	Packaging system
Cyclic	Packaging materials are cycled continuously through natural or (industrial) technical systems, minimizing material degradation and/or the use of upgrading additives.	Packaging material
Safe	Packaging components do not pose any risks to human health or ecosystems. When in doubt the precautionary component principle applies.	Packaging component

The definitions provided by the SPA and SPC offer a valuable starting point, representing significant steps toward a more coherent understanding

of sustainable packaging ([Dörnyei et al., 2023](#); [Grönman et al., 2013](#)).

Each definition criterion should be evaluated in relation to sustainable development principles and offer potential areas for improvement ([Boz et al., 2020](#)). Guidance for assessing the sustainability of packaging or sustainability commitments can be sourced from stakeholder-based organizations like the SPC or initiatives such as the Circular Economy goals of the American Chemistry Council (ACC) Plastics Division, the Materials Recovery for the Future program, the New Plastics Economy by the Ellen MacArthur Foundation, and the Ocean Plastics Charter ([Boz et al., 2020](#); Packaging Digest & [Sustainable Packaging Coalition, 2018](#)). Reaching a consensus on a deep, quantifiable definition of sustainable packaging is crucial for assessing the relative sustainability of one package compared to another ([Boz et al., 2020](#)).

[Dörnyei et al. \(2017\)](#) compiled a review of terminology used for sustainable packaging solutions and their definitions. They identified nine synonyms for “sustainable packaging,” 14 for “circular packaging,” 10 for “bio packaging,” and five for “other sustainable packaging.” Each of these will be discussed now.

12.2.1 “Sustainable Packaging” Category

Packaging solutions in this category incorporate the Triple Bottom Line (TBL) approach, addressing economic, social, and environmental impacts, integrated throughout the life cycle of the packaging material, in every stage of the supply chain from creation to disposal ([Jain & Hudnurkar, 2022](#)). Sustainable packaging inherently carries an environmental impact, making the terms “more” or “less” sustainable packaging more fitting ([Boz et al., 2020](#)). Alternatively, the notion of “sustainable packaging” could be reevaluated, as the concept of sustainability as an absolute value could be considered unrealistic or idealized ([Dörnyei et al., 2023](#)). Furthermore, sustainable packaging often focuses on reducing the *direct* environmental consequences of the use of the materials through prioritization of minimizing material use (e.g., avoiding unnecessary packaging or

overpackaging) and single-use plastics rather than addressing food waste reduction, which is less directly considered ([Dörnyei et al., 2023](#)). [Dörnyei et al. \(2023\)](#) provide three definitions in this category.

The first definition is for “sustainable packaging” and states that the term “sustainable” applies the concept of sustainability to packaging production, encompassing product and packaging systems. It integrates the goals of sustainable development—economic, social, and environmental—across each stage of a package’s life cycle, from cradle to grave, in every stage of the supply chain. Sustainable packaging is thus seen as safe, healthy, market-efficient, and cost-effective, being sourced, produced, transported, and recycled with renewable energy sources and renewable or recyclable materials. It also uses clean production technologies, follows best practices, and is designed to optimize material and energy usage, making it effectively recoverable and reusable across multiple production cycles ([Boz et al., 2020](#); [Dörnyei et al., 2023](#); [Grönman et al., 2013](#); [Magnier & Schoormans, 2015](#); [Martinho et al., 2017](#); [Nordin & Selke, 2010](#); [Orzan et al., 2018](#)).

The second definition is for “environmentally friendly packaging,” with “eco-friendly packaging,” “ecologically responsible packaging,” “ecologically conscious packaging,” “pro-environmental packaging,” “ecologically packaged products,” and “eco-design(ed) packaging” listed as synonyms. These are all terms that relate to a packaging innovation strategy that aligns with the United Nations (UN) Sustainable Development Goals (SDGs), promoting a balanced approach to ecological, social, and economic progress. It minimizes environmental harm compared to traditional packaging, uses materials efficiently, reduces solid waste, and helps decrease food loss and waste. Typically designed based on life cycle assessment (LCA), this packaging embodies multiple sustainable attributes and explicitly or implicitly conveys eco-friendliness to consumers ([Dörnyei et al., 2023](#); [Ketelsen et al., 2020](#); [Koenig-Lewis et al., 2014](#); [Magnier & Crié, 2015](#); [Nguyen et al., 2020](#); [Prakash et al., 2019](#); [Prakash & Pathak, 2017](#); [Scott & Vigar-Ellis, 2014](#); [Yokokawa et al., 2018](#); [Zeng et al., 2020](#); [Zeng et al., 2021](#); [Zeng & Durif, 2020](#)).

The third definition is for “green packaging.” *Green packaging* emphasizes its reduced impact on waste and pollution and utilizes ecological materials or employs manufacturing methods that avoid potentially harmful substances for human health and the environment ([Ahmed & Varshney, 2011](#); [Dörnyei et al., 2023](#); [Wandosell et al., 2021](#)).

While terms like “environmentally friendly packaging” and “green packaging” are frequently used as synonyms for sustainable packaging, they are not necessarily always synonyms ([Dörnyei et al., 2023](#)).

12.2.2 “Circular Packaging” Category

Packages in this category are designed following circular economy principles. Terms like recyclable, recycled, reusable, and zero waste are often interpreted similarly and are therefore commonly grouped together ([Dörnyei et al., 2023](#)). Circular packaging represents an approach to sustainability by limiting new resource inputs into the system. While often viewed as a subcategory of sustainable packaging, it focuses primarily on life cycle (resource cycles) and the material’s end-of-life ([Testa et al., 2020](#)), even though avoidance should remain the top priority in the decision tree ([Dörnyei et al., 2023](#)). Reintroducing materials to avoid virgin resource use can sometimes be expensive or difficult to verify as safe ([Nerín et al., 2022](#); [Tsochatzis et al., 2022](#)). Practices within the circular packaging definition include reusing, mechanical recycling, and chemical recycling, while the material’s origin (e.g., renewable vs. fossil-based) and the resources consumed (e.g., energy, raw materials) are not considered in the definition. End-of-life options vary as well: compostable materials, for instance, may require either simple home composting or more complicated industrial composting, and recycling may involve chemical or mechanical processes that sometimes degrade material quality. Additionally, the specific functions (e.g., protection) that the packaging material may provide to the food are not referenced in circular packaging definitions ([Dörnyei et al., 2023](#)). [Dörnyei et al. \(2023\)](#) provide four definitions in this category.

First, “circular packaging” is defined, with “zero-waste packaging” listed as a synonym. *Circular packaging* is crafted to align with circular economy principles—incorporating recycled content, reusability, design for disassembly, and recyclability—to conserve natural resources, optimize their use, and reduce environmental harm. *Zero-waste packaging* emphasizes maintaining a closed-loop material flow that generates no waste, though it is sometimes mistaken for “zero landfill.” In zero-waste packaging systems, materials are also repurposed, repaired, or redistributed within the system at their end-of-life ([Dörnyei et al., 2023](#); [Jäger & Piscicelli, 2021](#); [Song et al., 2015](#); [Testa et al., 2020](#)).

The second definition is for “recyclable packaging.” In a similar vein, *recyclable packaging* consists of materials that can be reintroduced into the production cycle through disposal, collection, sorting, and either mechanical or chemical reprocessing. This definition does not account for the economic efficiency of the recycling process or whether the material undergoes downcycling ([Dörnyei et al., 2023](#); [Muranko et al., 2021](#); [Wang et al., 2021](#)).

The third definition is for “recycled packaging,” with “post-consumer recycled content packaging,” “ocean plastic packaging,” and “beach plastic packaging” listed as synonyms. *Recycled packaging* is produced from recycled materials, such as post-consumer recycled (PCR) content or ocean plastic, thereby reducing the need to use new, virgin materials ([Dörnyei et al., 2023](#); [Magnier et al., 2019](#); [Van Sluisveld & Worrell, 2013](#)).

The fourth definition is for “reusable packaging,” with “closed-loop packaging,” “returnable packaging,” “multi-way packaging,” “non-disposable packaging,” “durable packaging,” and “refillable packaging” listed as synonyms. *Reusable packaging* is packaging that serves as a waste management strategy that integrates forward distribution operations with reverse logistics, allowing products or components to be handled, stored, and transported for reuse in their original purpose. This approach reduces the need for new materials ([Accorsi et al., 2020](#); [Böröcz, 2023](#); [Dörnyei et al., 2023](#); [Dubiel, 1996](#); [Muranko et al., 2021](#); [Van Sluisveld & Worrell, 2013](#); [Vöröskői et al., 2020](#)).

12.2.3 “Bio-Packaging” Category

This category of sustainable packaging is diverse and somewhat loosely defined since the category includes packages labeled as “bio-based,” “biodegradable,” “oxo-degradable,” or “compostable,” which all have varied meanings. These terms highlight the packaging material’s source (i.e., renewable sources (e.g., second-generation feedstocks) or fossil-based) and/or its ability to degrade. While bio-packaging could be considered a subcategory of sustainable packaging, it is a broad group and assessing the environmental benefits of bio-packaging is important to determine its true sustainability. This involves considering end-of-life degradability and material origin, especially in the case of biomass waste and residues, as the use of these has the potential to displace food crops ([Cruz et al., 2022](#)).

Therefore, such terms can create significant confusion, not only among consumers, and the misunderstandings that result have the potential to cause a risk to the environment over time. Bio-based plastics, for instance, may not always be biodegradable, whereas the name may suggest otherwise. [Dörnyei et al. \(2023\)](#) provide four definitions in this category.

The first definition is for “bio-based packaging,” with “plant-based packaging,” “biomaterial-based packaging,” “bioplastic packaging,” “biopolymer packaging,” and “bio-packaging” listed as synonyms. *Bio-based packaging* refers to materials that are either bio-based (made from renewable raw materials obtained from biological resources, such as agricultural or marine sources, including microbial cellulose, polyhydroxyalkanoates, polysaccharides, proteins, lipids, and/or resins) or biodegradable or possess both properties. It also includes biodegradable materials or those that are bio-based but not necessarily recyclable or biodegradable, or fossil fuel-based but still biodegradable ([Cruz et al., 2022](#); [Cutter, 2006](#); [Dörnyei et al., 2023](#); [Gontard & Guilbert, 1994](#); [Lomartire et al., 2022](#); [Reichert et al., 2020](#); [Santhosh et al., 2021](#)).

The second definition is for “biodegradable packaging,” with “oxo-degradable packaging” listed as a synonym. *Biodegradable packaging* “describes alternative end-of-life scenarios for packaging materials where

its breakdown occurs via industrial or home-composting.” This definition also applies to fossil fuel-based packaging that can biodegrade ([Allison et al., 2021](#); [Cruz et al., 2022](#); [Dörnyei et al., 2023](#); Ivonkovic et al., 2017; [Reichert et al., 2020](#); [Zaborowska et al., 2021](#)).

The third definition is for “compostable packaging.” *Compostable packaging* refers to “materials which break down and degrade in the environment but consists of only organic elements that degrade in the environment without leaving any toxic residue.” This definition notes that while all compostable materials are biodegradable, not all biodegradable materials are compostable ([Allison et al., 2021](#); [Dörnyei et al., 2023](#); [Reichert et al., 2020](#)).

The fourth definition is for “edible packaging (films, coatings).” *Edible packaging* is “a wrapping or coating that is an integral part of the (food) product, fully degradable and can be eaten with the product” ([Cutter, 2006](#); [Dörnyei et al., 2023](#); [Janjarasskul & Krochta, 2010](#); [Kadzińska et al., 2019](#); [Petkoska et al., 2021](#)).

12.2.4 “Other Sustainable Packaging” Category

This category encompasses packaging solutions that address specific aspects of sustainability ([Lewis et al., 2007, 2010](#); [Santi et al., 2022](#)), focusing on effective, efficient, cyclic, and safe practices (the four principles that must be met to meet SPA’s definition of sustainable packaging) ([Dörnyei et al., 2023](#)). Examples include refillable, innovative, and lightweight packaging, which improve current practices. The function of these packages is also improved (e.g., minimizing food waste, reducing plastic litter, and enhancing waste sorting) and somewhat easily demonstrated to the end user. These solutions can be seen as a subcategory of sustainable packaging ([Dörnyei et al., 2023](#)). [Dörnyei et al. \(2023\)](#) provide four definitions in this category.

The first definition is for “(eco) refill packaging.” *(Eco) refill packaging* is defined as packaging that extends the lifetime of (parent) packaging by using a secondary, lighter, and more flexible packaging, while still being

considered as a supplementary one-way product ([Dörnyei et al., 2023](#); [Van Sluisveld & Worrell, 2013](#)).

The second definition is for “non-excessive packaging.” *Non-excessive packaging* refers to “a packaging redesign, where abundant components are removed without compromising other packaging functions, quality, and esthetics” ([Dörnyei et al., 2023](#); [Van Sluisveld & Worrell, 2013](#)).

The third definition is for “lightweight packaging,” with “downgauging packaging” listed as a synonym. *Lightweight packaging* is packaging that “decreases the external dimensions of packaging, while maintaining similar inner dimensions, while offering the same or an enhanced packaging strength [e.g.: reducing the average thickness of the original material; replacing original material for a more lightweight alternative (composite)]” ([Dörnyei et al., 2023](#); [Van Sluisveld & Worrell, 2013](#)).

And the final definition is for “innovative packaging.” *Innovative packaging*

includes novel materials in mono- or multilayers while decreasing the environmental pressure by considering a broad range of sustainability issues (e.g.: waste prevention, efficient use of resources, process optimization, recycle, reuse). Innovative packaging is more of a design and holistic approach.

([Dörnyei et al., 2023](#); [Reichert et al., 2020](#); [Vanderroost et al., 2014](#))

12.3 CONSUMERS OF SUSTAINABLE PACKAGING

Some of the main factors that influence purchasing decisions about sustainable packaging are demographics, education, country of origin, value-action gap, and media coverage (see [Table 12.2](#)).

TABLE 12.2 Factors Influencing Consumers When Making Purchasing Decisions on Sustainable Packaging 

<i>FACTOR</i>	<i>DESCRIPTION</i>	<i>REFERENCE</i>
Gender and Age	Most of the studies showed that older generations are less inclined to purchase sustainable packaging. Millennials and Gen Z are more likely to buy sustainable packaging and sustainable products. For gender, marketers are moving away from gender-based promotional tactics.	Nichols & Holt, 2023
Education	It has been shown by plenty of studies that consumers with a higher level of education tend to be more accepting of novel technologies such as sustainable packaging. Consumer participation improves consumers' willingness to pay more even when they exhibit low sustainability-oriented motivation (environmental concern) and ability (eco-literacy).	Giacalone & Jaeger, 2023 ; Popovic, Bossink & van Der Sijde, 2019 ; Tüzemen & Kuru, 2018
Country and Region of Origin	The differences in consumer behaviors on sustainability are also a function of the country and region of origin.	Wikström et al., 2016 ; Boz et al., 2020
Willingness to Pay	There is a positive willingness to pay for some packaging alternatives that consumers perceive to be sustainable. Moreover, consumers are generally dissatisfied with the current situation regarding unnecessary plastic packaging. If consumers believe that their purchase of a product with sustainable packaging	Herrmann et al., 2022

<i>FACTOR</i>	<i>DESCRIPTION</i>	<i>REFERENCE</i>
	would make a positive impact on the specific issue, this drives the choice toward sustainable packaging.	
Media Coverage	Consumers' understanding of sustainability changes due to media coverage and a greater societal emphasis on sustainability issues.	Hanss & Böhm, 2012 ; Nichols & Holt, 2023

12.3.1 Age and Gender

It is well known that the demographics including age, gender, education, and income levels may have either positive or negative effects on promoting sustainable purchase behaviors ([Chekima et al., 2016](#)). There are plenty of studies that evaluate consumer demographics as an influencing factor affecting purchasing decisions on sustainable packaging. For example, one study researched consumers' willingness to pay for the recyclability of the packaging of different materials including aluminum, glass, plastic, and paper and how this willingness was affected by demographics, including age, political party affiliation, and other non-demographic factors like limitations to recycling, including time-sensitivity. The study's results showed the consumers with higher education and females had a higher willingness to purchase ([The Sustainable Packaging Coalition, 2022](#)). A more recent study evaluated age and gender as factors affecting consumers when making purchasing decisions. The study had a sample of 1,250 participants in the United States. Overall, the results from the study showed that baby boomers have less favorable attitudes toward sustainability and place lower importance on sustainability when making purchasing decisions compared to the younger generations. Millennials and Gen Z are more likely than other generations to have sustainability attitudes, intentions, and behaviors. Similarly, while the present results support previous studies with respect to the main effects of gender, this

study finds that these gender differences, where women have more positive feelings toward sustainability, may be contextualized by the generational cohort, particularly when considering consumer attitudes toward sustainability. This is an important finding as most researchers do not utilize gender when studying generational cohorts in the context of sustainability issues. Furthermore, some marketers are moving away from gender-based promotional tactics ([Nichols & Holt, 2023](#)).

12.3.2 Education

Education influences consumers when making purchasing decisions on sustainable packaging. It has been shown by different studies that consumers with higher levels of education tend to be more accepting of novel technologies such as sustainable packaging or food technologies independently of country of origin ([Giacalone & Jaeger, 2023](#)). Interest in sustainability and price varies across education levels and household incomes. Consumers with the lowest levels of education and income are more concerned with a product's purpose and price than with its packaging and its characteristics (e.g., environmental impact). In fact, research has demonstrated that consumers with higher education and income levels pay more attention to packaging and exhibit greater environmental consciousness ([Popovic et al., 2019](#); [Tüzemen & Kuru, 2018](#)). For example, one study measured the effects of packaging on consumers, considering environmental, health, quality, reusability, and recycling benefits. Researchers found that lower levels of education were associated with a greater focus on the product itself rather than its packaging. Conversely, consumers with higher education and income levels were more interested in packaging and demonstrated greater environmental consciousness, while consumers with lower education and income levels were more concerned with price ([Popovic et al., 2019](#)).

The price of a product with sustainable packaging could be higher due to the cost of materials and equipment used. It is well known that commodity materials (e.g., plastic, glass, paper) and the equipment used to manufacture

and assemble packaging are less expensive than innovative materials. This higher cost of materials and equipment is reflected in the product's price. Consequently, products with packaging made from innovative materials (e.g., sustainable packaging) are typically more expensive than those with packaging made from commodity materials. These higher prices influence consumer behavior and willingness to pay ([Walker et al., 2021](#); [Lindh, Olsson, et al., 2016](#)). Therefore, consumers with higher education and income levels, who have greater environmental consciousness, might be willing to pay a higher price for a product with sustainable packaging.

12.3.3 Country and Region of Origin

The differences in consumer behaviors surrounding sustainability are also determined by the country and region of origin ([Wikström et al., 2016](#)). Country and region of origin are consumer demographics that influence consumers when making purchasing decisions on sustainable packaging ([Herbes et al., 2018](#)). A study evaluating the country of origin as a demographic factor that affects consumers when making purchasing decisions on sustainable packaging revealed that, besides cross-cultural differences, significant within-country variation was also evident ([Giacalone & Jaeger, 2023](#)).

12.3.4 Willingness to Pay

Regarding willingness to pay, there is a positive willingness to pay for packaging alternatives that consumers perceive to be sustainable, and there is willingness to pay for those alternatives that consumers perceive to be non-sustainable or that they are unsure about, specifically “bioplastic” packaging. In fact, a study demonstrated that there is a great deal of uncertainty regarding the sustainability of bioplastic among consumers and that they perceive bioplastic as greenwashing rather than a sustainable alternative to conventional plastic. Going hand in hand with these insights, there is no willingness to pay for bioplastic packaging. Moreover, consumers are generally dissatisfied with the current situation regarding

unnecessary plastic packaging ([Herrmann et al., 2022](#)). Furthermore, if consumers believe that their purchase of a product with sustainable packaging would make a positive impact, they're willing to buy the product ([Valor, 2008](#)). This willingness to purchase can be affected by factors such as personal motivation and information available ([Boz et al., 2020](#)). Consequently, it is critical that CPGs educate and inform consumers about sustainable packaging and how they are making a positive impact on the environment and the world.

However, these facts should not be a limitation when planning to launch a product with sustainable packaging for the majority of the population that does not align with these factors. It is well known that willingness to pay more for sustainable products is a key barrier that impedes purchasing of a sustainable product. In fact, little is known about what firm-initiated actions can be taken when consumers do not possess characteristics that favorably influence green purchasing behaviors. A research study demonstrated that consumer participation improves consumers' willingness to pay more even when they exhibit low sustainability-oriented motivation (environmental concern) and ability (eco-literacy). For example, when low eco-literacy is the predominant impediment to purchasing sustainable products, the marketing experts should focus their consumer participation initiatives on helping consumers build a sense of competence and efficacy beliefs ([Wei et al., 2018](#)). Therefore, consumer education can influence them when making purchasing decisions. In the United States and Canada, there is a well-known organization for consumer education called How2Recycle that is part of Green Blue, the nonprofit organization that also contains the Sustainable Packaging Coalition. The How2Recycle label is based on nationally harmonized data and provides consistent and transparent on-package disposal instructions for consumers. Moreover, these labels are developed based on a recyclability assessment of all the packaging materials and components, such as inks and adhesives. How2Recycle is trying to stay on top of all the new environmental regulations that involve packaging such as EPR bills. For now, the How2Recycle label is aligned with legislation in the United States and Canada, including the Federal

Trade Commission's Green Guides and Canada's Competition Bureau guidelines ([How2Recycle, 2024](#)).

12.4 CONSUMER PERCEPTION

The marketing strategies employed by CPG companies have played a significant role in influencing preferences across categories (e.g., food and beverage) and reshaping the cultural values that guide behaviors. For example, food companies have been instrumental in redefining dietary norms. Additionally, CPG companies in Europe are influencing consumer behavior regarding sustainable packaging due to EPR regulations. These factors collectively impact consumer decisions and the broader adoption of sustainable practices ([Atta-Delgado et al., 2024](#); [Vermeir et al., 2020](#)). Furthermore, academic, government, and industry researchers are developing sustainable solutions aimed at reducing the environmental impact of packaging waste. These solutions help minimize the use of petroleum-based materials, lower chemical hazards, and decrease household waste. They are generally formulated using biopolymers such as proteins, polysaccharides, lipids, and other biodegradable components ([Atta-Delgado et al., 2024](#)). These initiatives significantly influence consumer behavior and perceptions. On the other hand, consumer perception is a critical factor that must be considered when launching a new product, especially if the product features sustainable packaging. For instance, a CPG company considering the launch of a product with sustainable packaging to reduce environmental impact must conduct consumer research to understand consumer behavior, acceptance, and perceptions of the new packaging. While the company's intention may be to reduce environmental impact and comply with environmental laws, consumers might perceive the sustainable packaging as greenwashing or evidence of a lack of transparency from the company.

Therefore, it is essential to account for consumer perception when conducting research before launching a product. Studies should analyze consumer behavior (e.g., attitudes and social norms) ([Eichhorn & Meixner, 2020](#); [Paul et al., 2016](#)), economic and management factors (e.g., price, brand value, and perceived quality) ([Liu et al., 2020](#); [Tsai et al., 2012](#)), and the characteristics of green consumer segments. Additionally, studies should examine the influence of specific sustainability features—such as ecological footprints, carbon emissions, and labels—on the choices of different consumer segments ([Song et al., 2019](#); [Wägeli & Hamm, 2016](#)). While these studies provide valuable insights into understanding green consumer markets, it remains unclear how companies can leverage these factors to enhance the performance of sustainable products in the face of competitors targeting consumer segments less sensitive to environmental issues ([Camilleri et al., 2023](#)).

12.4.1 Consumer Misconceptions about Sustainable Packaging

Sustainable packaging efforts are popular with most consumers, especially the new generations. However, most consumers still have misperceptions of sustainability in general ([Simpson & Radford, 2012](#)). The most critical challenge is that different definitions of sustainable packaging from regulations, academia, industry, and nonprofit organizations continue to evolve fast. Consumers often make decisions with insufficient information about sustainability, relying instead on cues and assumptions ([Boz et al., 2020](#)). From a consumer's perspective, sustainable packaging is often understood as “packaging design that evokes explicitly or implicitly the eco-friendliness of the packaging” ([Boz et al., 2020](#); [Magnier & Crié, 2015](#)). Consumers frequently judge the sustainability of a product based on the three Rs (Reduce, Reuse, and Recycle) ([Oloyede & Lignou, 2021](#); [Ruiz-Real et al., 2018](#)). If consumers are able to identify sustainable packaging, they often associate it primarily with the environmental pillar of sustainability and they tend to forget about the other critical pillars, social and economic ([Boz et al., 2020](#)). For example, consumers might think a

package is sustainable if the packaging contains a recycling label. However, they might not think about how the company is putting efforts into the social and economic aspects of sustainability. This perspective creates a significant gap between consumer perceptions and scientific reality. Research indicates substantial discrepancies between life cycle assessment (LCA) results and how consumers rank sustainable traits ([Boz et al., 2020](#); [Steenis et al., 2017](#); [Tobler et al., 2011a](#); [Van Dam, 1996](#)). For the sustainable development of the packaging industry, it is essential for consumers to understand the outcomes of LCAs, which evaluate the true environmental impact of packaging by assessing all stages from production to disposal. Unfortunately, consumer judgments frequently diverge from LCA findings ([Boz et al., 2020](#)). This disparity highlights that consumer perceptions of what constitutes a sustainable package often diverge from the actual sustainability of the packaging ([Boz et al., 2020](#)).

Another layer of confusion stems from the misunderstanding of key terms like “biodegradable” and “bio-based,” with many consumers struggling to comprehend the nuanced differences between such terms. For instance, the term “bio” in packaging is often interpreted by consumers to mean that bioplastics are readily biodegradable in the environment. In reality, most of the commercially available biodegradable polymers only break down in controlled industrial composting systems, and some bio-based plastics are not biodegradable at all ([Boz et al., 2020](#); [Guillard et al., 2018](#)).

Furthermore, a review of 38 terms reveals that literature employs an excessive number of terms, many of which are highly similar (e.g., synonyms such as “environmentally friendly,” “eco-friendly,” “ecologically responsible,” “ecologically conscious”), resulting in superficial definitions that often lack applicability beyond their specific contexts. The definitions emphasize the three pillars of sustainability—environmental, social, and economic capital ([Hansmann et al., 2012](#))—unevenly, with a predominant focus on environmental aspects ([Dörnyei et al., 2017](#)). Furthermore, minimal attention is given to the roles and responsibilities of key stakeholders, such as consumers and managers. Additionally, these terms

often fail to establish a meaningful connection between the packaging and the product, which is particularly critical in the food sector. The use of technical terminology can create communication barriers, making it challenging for the public—including consumers, journalists, and managers—to comprehend, assess, and make informed decisions. Consequently, existing definitions of sustainable packaging are often overly complex and difficult to convey effectively. This lack of clarity, combined with insufficient public understanding or willingness to engage with the information, may result in issues like “information overload” or, more critically, misleading communication of sustainable packaging (greenwashing) ([Dörnyei et al., 2017](#)).

12.4.2 Material Preferences and Misconceptions

Consumers increasingly view paper as an environmentally friendly, high-value packaging material due to its advantages of being recyclable, biodegradable, and bio-based ([Fernqvist et al., 2015](#); [Lindh et al., 2015](#); [Oloyede & Lignou, 2021](#); [Steenis et al., 2017](#)). Studies consistently rank paper, paperboard, paper-based or paper-wrapped products and glass packaging as the most sustainable options, ranking plastics and metals lower and overlooking crucial factors such as the sourcing and production processes that contribute to the overall environmental burden of paper and glass ([Allegra et al., 2012](#); [Boz et al., 2020](#); [Van Dam, 1996](#)). Participants of a study in Sweden called attention to the “negative environmental impact of plastic packaging,” and considered paper to be more environmentally friendly ([Fernqvist et al., 2015](#)). Additionally, when plastic, paper, glass, and metal were compared, consumers ranked paper and plastic as the most and least environmentally friendly materials, respectively ([Lindh et al., 2015](#); [Oloyede & Lignou, 2021](#); [Steenis et al., 2017](#)). Furthermore, in the study by [Oloyede and Lignou \(2021\)](#), several comments were made by participants (consumers) suggesting that the packages could be made more environmentally friendly by utilizing paper packaging: “instead of the black plastic tray, the biscuits could be in a cardboard box,” “polystyrene! Can’t it

be cardboard?,” “why not use paper packaging and have a window on the lid so the product is visible to consumers?”

However, life cycle assessments (LCA) often counter these views. For example, while glass is widely perceived as sustainable, its high production and transport impact result in a greater environmental burden than plastic in some cases. For example, in a study by [Steenis et al. \(2017\)](#), consumers ranked dry carton sachets, which have one of the lowest LCA impacts (<5%), as one of the least sustainable options. Meanwhile, glass jars, which have a much higher environmental impact (42%), were rated among the most sustainable materials due to their perceived reusability and recyclability ([Steenis et al., 2017](#)). Similarly, consumers mistakenly rate bioplastics as highly sustainable, despite their high environmental impact ([Boz et al., 2020](#); [Steenis et al., 2017](#)). Some participants of the study by [Oloyede and Lignou \(2021\)](#) perceived glass as more sustainable than plastic packaging. However, others did realize the high environmental cost of glass production, revealing a lack of consensus and confusion among consumers about what constitutes sustainability in food packaging ([Oloyede & Lignou, 2021](#)).

This disconnect highlights how limited consumer knowledge often leads to superficial judgments being mostly subjective and based on their personal perception rather than a holistic understanding of packaging sustainability ([Boz et al., 2020](#)). In fact, surveys have shown that consumers could not identify the sustainable packaging or did not have a clear idea of what sustainable packaging involves ([Lindh, Olson, et al., 2016](#); [Lindh, Williams, et al., 2016](#)), often defining a sustainable product based on “Reduce, Reuse, and Recycle,” or the “3Rs,” which are important processes within the Circular Economy ([Ruiz-Real et al., 2018](#)). Moreover, consumers often have limited to no understanding of how packaging’s production, transportation, and retail processes contribute to its overall sustainability ([Boz et al., 2020](#); [Herbes et al., 2018](#)). By focusing solely on the mode of post-consumption utilization, consumers often overlook the production aspect of packaging when judging the sustainability of a package ([Boz et al., 2020](#)).

For instance, reusable glass and plastics, along with paperboard, are frequently ranked as the most sustainable options, while non-returnable plastics, plastic, and paperboard portions are perceived as the least sustainable ([Boz et al., 2020](#)). In contrast, LCA studies rank materials like metal and plastic as sometimes more sustainable than consumer perceptions suggest. In a similar study, consumers ranked glass, paper-wrapped, and canned peas as the most sustainable packaging options, even though these materials had the highest environmental impacts when assessed through LCA ([Boz et al., 2020](#); [Van Dam, 1996](#)). Consistent findings in consumer research highlight that materials like metal and plastic packaging are often ranked as the least sustainable options, which contradicts LCA results ([Boz et al., 2020](#); [Tobler et al., 2011b](#)). This ongoing disconnect underscores the need for better consumer education regarding the comprehensive sustainability of packaging materials to improve knowledge of sustainability and sustainable habits of society as a whole ([Carvalho et al., 2022](#)).

Moreover, it is worth noting that the visibility of the packaging itself may influence consumer perceptions of sustainability, as there is a direct effect of the packaging material on the visible environment ([Boz et al., 2020](#)). Therefore, many misconceptions arise due to what could be described as a “visibility bias” based on the visible aspects of the disposal of the actual packaging because consumers can directly observe the disposal of packaging. Proper disposal, such as using recycling bins, and improper disposal, such as littering on roadsides and in waterways, are both in the public eye ([Boz et al., 2020](#); [Van Birgelen et al., 2009](#)). For example, littered plastic bags and paperboard fast-food cartons represent just a small percentage of packaging, but their high visibility compared to the high environmental impacts associated with the production, collection, and recycling of materials like glass bottles ([Boz et al., 2020](#)) perpetuates the negative perceptions of these materials.

12.4.3 Greenwashing

This confusion is compounded by marketing claims that sometimes exaggerate or obscure the true sustainability of packaging, a practice known as greenwashing ([Boz et al., 2020](#)). Greenwashing has become increasingly prevalent in recent years, with reports showing a 200% increase in greenwashing marketing on labels between 2009 and 2010 ([Boz et al., 2020](#); [Terrachoice, 2010](#)). This includes the use of terms like “eco-friendly,” symbols like a green leaf, or even the color green itself to suggest that a package is more environmentally responsible than alternatives ([Boz et al., 2020](#)). Greenwashing undermines consumer trust, creating false impressions about the environmental benefits of packaging ([Boz et al., 2020](#); [Gutierrez & Thornton, 2014](#); [Jerzyk, 2016](#); [Magnier & Cri , 2015](#)). As a result, some consumers have become skeptical of sustainability claims, further complicating the adoption of truly sustainable packaging solutions. This hesitation stems from a real or perceived high risk in promoting sustainable packaging, as it is often associated with previously misleading claims. The fear of being accused of greenwashing has led some companies to scale back or abandon their sustainability messaging altogether ([Boz et al., 2020](#); [Terrachoice, 2010](#)). Brands worry that any environmental claim, even if accurate, could be met with skepticism, “greenwashing” accusations, or other forms of backlash ([Boz et al., 2020](#)). This hesitation prevents some companies from promoting their eco-friendly initiatives, further complicating the adoption of truly sustainable packaging solutions ([Boz et al., 2020](#); [Terrachoice, 2009](#)). As a result, legitimate brands offering truly sustainable packaging may lose their competitive edge due to consumer distrust, which has been fueled by past instances of greenwashing ([Boz et al., 2020](#)). For example, research shows that simply using the color green on packaging, without any accompanying environmental claims, can negatively affect how consumers perceive the product’s effectiveness ([Boz et al., 2020](#); [Pancer et al., 2017](#)).

The opportunity to couple package sustainability with sales has also led to the sustainability efforts within the food packaging industry to become misguided ([Boz et al., 2020](#)). [Peattie and Crane \(2005\)](#) pointed out several common failures in green marketing, such as pricing regular products as

premium, focusing only on promotional aspects without meaningful product development, and concentrating on compliance rather than true sustainability. Starting in the 1990s, behavioral research began influencing how sustainability was integrated into marketing efforts, yet these efforts often resulted in ambiguous or even false “green” claims ([Boz et al., 2020](#)). Terms like “TerraCycling,” which lack clear definitions, further confuse consumers, leading to misunderstandings about the sustainability of packaging ([Boz et al., 2020](#)).

This inability to communicate clearly to consumers has resulted in missing essential information for informed decision-making, causing confusion about packaging sustainability ([Boz et al., 2020](#)). This has hindered consumers’ ability to make informed, fact-based decisions about the sustainability of packaging, particularly in countries without extended producer responsibility (EPR) systems. In contrast, countries with EPR mandates, like those in the EU, provide consumers with intrinsic and consistent information about the costs associated with packaging disposal—whether through recycling, reuse, landfilling, composting, or degrading—through the EPR process ([Boz et al., 2020](#); [European Commission, 2015](#)).

12.4.4 Expectations from Sustainable Packaging

[Oloyede and Lignou \(2021\)](#) conducted a qualitative study investigating consumers’ expectations and opinions of sustainable paper-based packaging materials. Participants were asked to discuss expectations from a sustainable package; the main expectations mentioned by participants are summarized as follows:

1. *“Functionality in terms of maintaining product quality (e.g., freshness) and shelf life”*: Participants felt “it should do its work of keeping the product safe and maintaining its quality.” Resealability and reusability were also attributes that participants mentioned would be preferred to make a sustainable package.
2. *“Durability”*: Participants felt “it should be strong, stress-resistant, and able to keep the product intact without splitting or breaking until I

get to my destination.”

3. “*Aesthetic value*”: Participants felt “the design should be very attractive and stand out from other less sustainable packages.”
4. “*Must be recyclable or biodegradable*”: Participants felt “a sustainable package should be easy to recycle and would be better if it was 100% recyclable,” and “there is no point in me buying an attractive package if it is not recyclable.”
5. “*Minimal amount of packaging should be used*”: Participants commented, “Do not over package products; use just enough packaging required to maintain product quality and safety.”

Despite being made from sustainable paper-based materials, participants in the study perceived the oversized packaging as wasteful and environmentally harmful. This view suggests that the amount of packaging should be proportionate to the product size to avoid unnecessary material use. A study by [Hanssen et al. \(2017\)](#) also found that participants thought that the manufacturers used too much packaging, with over 50% of the participants sharing this view. The consumer view that minimizing packaging and avoiding unnecessary packaging has a strong positive environmental impact is also seen by [Tobler et al. \(2011a\)](#) and [Lea and Worsley \(2007\)](#). However, consumers did not always consider the amount of packaging to be an important factor ([Oloyede & Lignou, 2021](#); [Young, 2010](#)). The range of consumer perspectives reveals different views on what makes packaging environmentally friendly. As manufacturers transition to sustainable options, they should consider package size, as oversized packaging is seen negatively by consumers and often detracts from its sustainable appeal ([Oloyede & Lignou, 2021](#)).

6. “*Packages need to be clearly labeled for sustainability*”: Participants of the [Oloyede and Lignou \(2021\)](#) study said, “The sustainability message needs to be clear so consumers can easily see that the package is more sustainable than other packages.” This view was also seen by [Fernqvist et al. \(2015\)](#), who stated that “poor communication of the

added benefit of a product may influence consumer expectations and future purchase intent negatively.”

12.4.5 Needs for the Future and Communication

The study by [Oloyede and Lignou \(2021\)](#) revealed that the theme highlighted across focus group sessions was the confusion on how to handle packages, with more education needed. Key comments included: “most consumers do not understand how recycling works; do packages need to be washed before disposing them in the recycling bin?”; “clearer directions from manufacturers on how to dispose packaging is necessary”; and “more universal methods of disposing packages are necessary.” The participants of the study called for full transparency of the packaging process with comments like “we don’t have the full story,” and “consumers need information on things like the carbon footprint of packaging materials.”

In order to avoid misperceptions from consumers and greenwashing, education is key. Education has been a critical component when developing public health campaigns in the United States (e.g., improve lifestyles, stop smoking, increase milk consumption) during the past 30 years. Any consumer education strategy should include industry, government, and nongovernmental organizations. The strategy must include three critical domains: brand development, marketing execution, and evaluation and outcome reporting ([Englund et al., 2020](#)).

Effective consumer education requires accurate, clear, and concise information on packaging, which is essential for promoting sustainable packaging as part of a successful consumer education strategy. Moreover, this information should be perceived as trustworthy and be culturally aligned to the market region or country ([Herbes et al., 2020](#)). To enable an understanding about the information provided in the packaging, governments must invest in a communication strategy with advertisement campaigns aimed at instructing consumers about how, where, and why they should properly dispose of their garbages and their destinations ([Nascimento et al., 2014](#)). Therefore, it is essential to develop strategies

aimed at reducing the impact of packaging waste to encourage consumers to demand and take environmentally accountable actions ([Herbes et al., 2020](#); [Carvalho et al., 2022](#)). This communication strategy should be aligned with the environmental regulations. Furthermore, the effectiveness and compliance of environmental regulations must include the provision of infrastructure (e.g., recycling centers, collection programs) as well as a communication strategy to inform consumers.

Acceptability of sustainable packaging systems by consumers is a process affected by many factors. For example, when consumers are exposed to novel food packaged products for the first time, they often make decisions based on the visual cues, such as packaging, before tasting them ([Baptista & Schifferstein, 2023](#); [Mehta et al., 2024](#)). Therefore, extrinsic product factors such as packaging material, color, and nutritional information significantly influence purchase decisions ([Naranjo-Guevarra et al., 2023](#); [Mehta et al., 2024](#)). However, these extrinsic factors alone do not guarantee repeated purchases of the novel products. Consequently, evaluating consumer behavior toward novel products can provide valuable and critical insights to understand the factors influencing the acceptability and purchasing decisions of new products. Products with sustainable packaging are novel products that must be evaluated for consumer insights to understand the acceptability as part of marketing and product development strategies.

The extrinsic and intrinsic attributes of a product affect consumers' behavior and acceptability ([Acebrón & Dopico, 2000](#); [Piqueras-Fiszman & Spence, 2014](#)). Both extrinsic and intrinsic characteristics significantly influence consumer attitudes and behaviors toward the product's liking and acceptability ([Valero-Cases et al., 2023](#)). Extrinsic characteristics refer to elements related to the product but are not physically a part of the product, such as packaging, country of origin, and price ([Liang et al., 2023](#)). In contrast, intrinsic characteristics, such as taste, flavor, and texture, are inherent to the product and cannot be altered without changing the product's physical properties ([Brečic et al., 2017](#)) (see [Figure 12.2](#)).

From the extrinsic characteristics, packaging is the characteristic that can be modified to reduce the environmental impact. It is well known that packaging has become essential to our daily lives, allowing us to protect and extend the shelf life of a product. Different packaging materials, such as plastic, glass, and metal, were developed many decades ago, and their capabilities are widely known. For example, plastic packaging production has increased in the past 50 years due to advantages such as low cost, durability, versatility, light weight, and shelf life extension ([Plastics Europe, 2023](#)). As consumer trends regarding sustainable packaging and environmental regulations evolve rapidly, more efficient and viable research should be conducted to study consumer behavior, particularly in CPG companies that operate in various states across the United States and different countries. As mentioned before, consumer behavior toward sustainable packaging is affected by factors such as age, gender, and country/region of origin. Moreover, the environmental regulations (e.g., EPR bills) in different states of the United States, countries in the European Union, and other countries in the world are promoting packaging with less environmental impact. Research about consumer acceptability and willingness to buy or purchase products and packaging with less environmental impact has been previously relatively well studied with different results ([Oloyede & Lignou, 2021](#)).

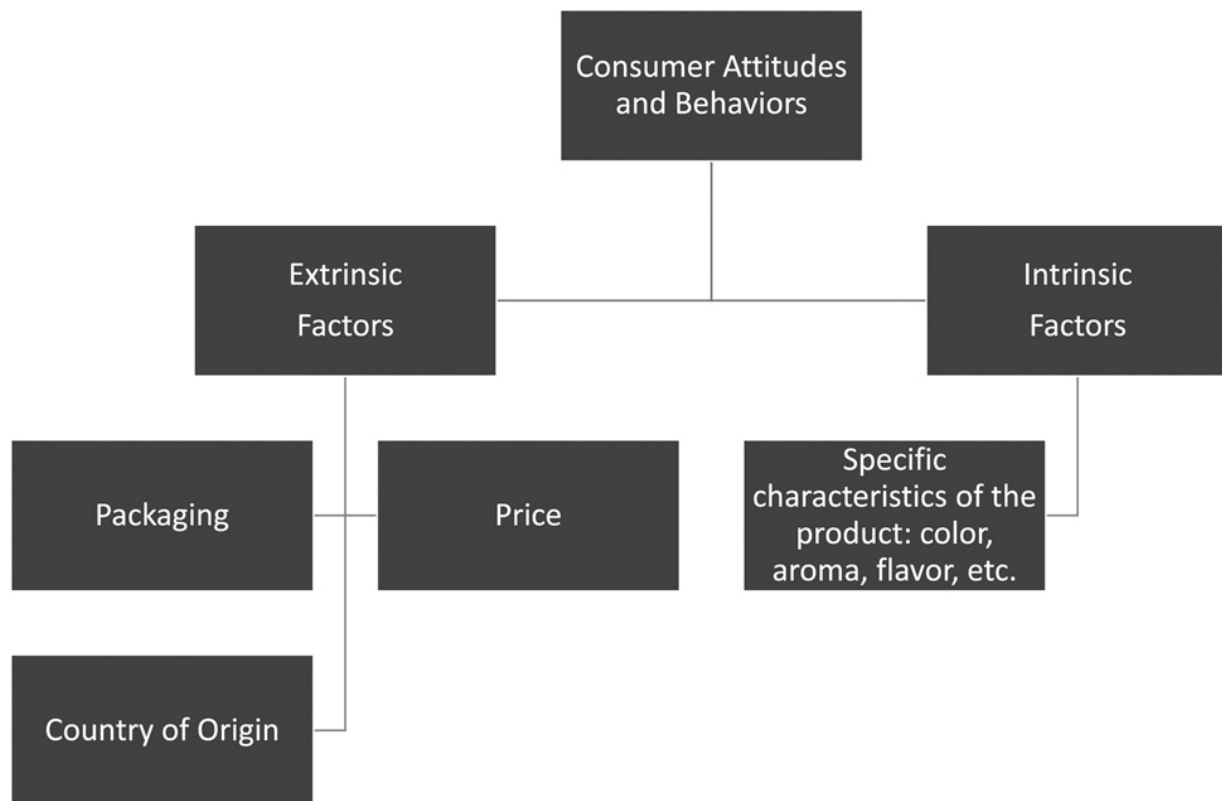


FIGURE 12.2 Extrinsic and Intrinsic factors influencing consumer attitudes and behaviors. Source: Mehta, 2024. [↗](#)

One of the challenges when measuring consumer behavior and acceptability of sustainable packaging systems is that the self-reported scales are vulnerable to misreporting, specifically overreporting pro-environmental behavior. Consequently, it is critical to measure the mechanisms of bias (e.g., social norms bias, social identity bias, and intention bias) in self-reports and develop techniques to reduce the bias ([Koller et al., 2023](#)).

Another challenge is that the research about consumer behavior and acceptability of specific packaging solutions is very limited; there are a few studies about specific packaging solutions such as paper packaging for cereal bars ([Ertz et al., 2017](#)), glass packaging for foods ([Singh & Pandey, 2018](#)) and for milk ([Neill & Williams, 2016](#)), and various packaging materials for tomato soup products ([Steenis et al., 2017](#)). This shows that existing knowledge on consumer responses to specific sustainable

packaging solutions is limited. As a result, to better understand consumer behavior and acceptability toward sustainable packaging, the research should be narrowed to a specific product and a specific packaging solution. For example, [Oloyede and Lignou \(2021\)](#) evaluated five paper-based prototype packages for two product categories, biscuits and meat, with 60 participants. The main results showed consumers mentioned “too much plastic” and “over-packaging” as some of the key issues of the current packaging. While participants were impressed by the sustainable nature of the prototype samples, the design did not necessarily meet their expectations, and they were not willing to pay more for a sustainable package. From discussions with the consumer participants, the key message that emerged was that the “3 Rs”—Reduce, Reuse, and Recycle—should be the main points to consider when designing sustainable packaging. This study shows that sustainable packaging is perceived by consumers as the “3 Rs,” when in reality, sustainable packaging encompasses more characteristics.

12.5 CONCLUSION

Materials and technologies to develop sustainable packaging are evolving fast. Moreover, consumers are demanding more sustainable solutions, and regulations in many different countries are promoting these technologies. Packaging companies are developing new materials and technologies. CPG companies are creating strategies to incorporate more sustainable packaging in their product portfolio. Both types of companies are planning for new environmental regulations and efforts to comply with them. On the other hand, the market is changing as the new generations have more purchasing power, demanding more sustainable packaging solutions. The research has shown a gap between what consumers believe versus what the reality is surrounding sustainable packaging. To bridge this gap, companies should add more consumer education for sustainable packaging to their marketing

campaigns. According to the audience preference, various platforms for this education could be pursued, such as social media, text messages, on package labels, and QR codes. If a CPG company wants to launch a new sustainable product or packaging, the company should conduct consumer research on behavior, preferences, and acceptability in order for a sustainable product to be successful in the market.

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